



Università degli Studi di Padova

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Scuola di Dottorato in Scienze della Terra
Ciclo XX

SEISMIC NOISE AND CONTROLLED
SOURCE SURVEYS: TOOLS FOR SEISMIC
HAZARD DETERMINISTIC APPROACH
(Field measurements in Venice Plain, Italy)

Direttore della Scuola : Chiar.mo Prof. Bernardo Cesare

Relatore: Chiar.mo Prof. Vittorio Iliceto

Correlatore: Chiar.mo Prof. Giuliano Francesco Panza

Dottorando: Jacopo Boaga

DATA CONSEGNA TESI
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*“There are two possible outcomes in any research:
If the result confirms the hypothesis,
then you've made a measurement.
If the result is contrary to the hypothesis,
then you've made a discovery”.*

E. Fermi

A mia madre

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RIASSUNTO

Questo lavoro si propone di studiare la pericolosità sismica di un' area della pianura settentrionale della provincia di Venezia (Nord Italia). Lo studio della risposta sismica locale è intrinsecamente multidisciplinare e coinvolge quindi discipline come la geologia, la geofisica, la sismologia e l'ingegneria. Il punto fondamentale di partenza è il modello geologico dell'area mentre la caratterizzazione fisica dei litotipi è compito della geofisica e dell'ingegneria geotecnica. La sismologia valuta i parametri fisici delle sorgenti sismiche, la propagazione delle onde nei mezzi e la loro interazione con le geometrie del sottosuolo. L'ingegneria utilizza i parametri dello scuotimento sismico per progettare infrastrutture in grado di sopportare le forze coinvolte.

Scopo di questa Tesi è descrivere, per l'area di interesse, uno scenario realistico di scuotimento sismico utilizzando un approccio deterministico. Tale approccio è in grado di calcolare lo scuotimento del suolo nella sua completezza, una volta che si è definito un modello di sottosuolo e una o più sorgenti sismiche. La capacità di poter valutare lo scuotimento dovuto a qualsiasi terremoto, anche storico, è di fondamentale importanza per l'area in studio, solo nel passato interessata da violenti terremoti, e di cui dunque non disponiamo di registrazioni strumentali.

In principio è stata necessaria una valutazione della sismicità storica dell'area e dei terremoti più forti in essa occorsi. Questa procedura ha anticipato una campagna di acquisizioni sismiche, che ha permesso di parametrizzare al meglio il sottosuolo, al fine di ottimizzare la definizione dei modelli.

Come primo passo è stata svolta una ricerca in letteratura volta all'approfondimento della conoscenza dell'area in studio. Sono stati utilizzati diversi studi geologici, geofisici e dati provenienti da sondaggi meccanici. Di notevole importanza si sono rivelati i non recenti studi per lo sfruttamento di idrocarburi (AGIP) e di acque termali. Nell'area sono stati difatti condotti studi gravimetrici, indagini strutturali, prospezioni sismiche a riflessione, e sondaggi profondi. Tutti gli studi pregressi hanno permesso di definire la struttura del sottosuolo con sufficiente dettaglio. Non erano invece disponibili informazioni

riguardo le velocità delle onde di taglio dei litotipi presenti, parametro fondamentale per la valutazione della risposta sismica locale. Si è sviluppata quindi una campagna di acquisizione sismica atta allo scopo.

Le ricerche sperimentali condotte durante questo lavoro sono state essenzialmente rivolte a tre obiettivi: confermare i dati pregressi della geometria del bedrock, registrare terremoti locali e, soprattutto, valutare le velocità delle onde di taglio dei litotipi presenti.

Per l'acquisizione dei terremoti locali sono state installate 2 stazioni sismiche in acquisizione continua per 6 mesi, una nella parte settentrionale dell'area in studio, una sulla estrema parte meridionale. Sono stati registrati 5 terremoti locali, 3 provenienti dalla zona sismogenetica potenzialmente più pericolosa (N-NE), un terremoto proveniente lateralmente da Est, ed un terremoto proveniente da Ovest. Le registrazioni hanno permesso di valutare le differenze di risposta sismica locale tra la parte settentrionale dell'area di studio e quella meridionale.

Per stimare la profondità del bedrock profondo, sono state eseguite delle campagne di acquisizione di rumore sismico a stazione singola. La tecnica HVSR è stata esclusivamente utilizzata per valutare il periodo proprio di vibrazione del sottosuolo, e derivare indirettamente una stima della profondità del contrasto di impedenza principale, associato al bedrock. La tecnica dei microtremiti è stata applicata anche per il riconoscimento del periodo proprio di vibrazione degli edifici.

Per valutare le velocità di taglio del sottosuolo è stata studiata la dispersione delle onde di Rayleigh, utilizzando la metodologia Frequency Time Analysis (Levshin et al. 1972, 1992). In particolare, durante il periodo di Tesi, si è sperimentato ed utilizzato il recentissimo sviluppo del nuovo software XFTAN, sviluppato dal Dr. F. Vaccari e dal gruppo di ricerca del Prof.G.F. Panza dell'Università di Trieste. L'analisi tempo-frequenza (FTAN) è stata applicata ai terremoti locali acquisiti, ed ha permesso di caratterizzare le velocità sismiche del bedrock profondo. Per studiare la dispersione delle onde superficiali nel corpo sedimentario, dello spessore di circa 500m, sono state impiegate sia prospezioni sismiche attive che passive. La sismica attiva si è avvalsa di diversi tipi di energizzazioni, quali cariche esplosive, masse battenti e fucili sismici. Il lavoro ha permesso di valutare con accuratezza le velocità delle onde di taglio del primo sottosuolo.

La sismica passiva, basata sulla cross-correlazione del rumore sismico, rappresenta l'applicazione più innovativa del lavoro svolto ed ha permesso di valutare le onde di taglio per il sottosuolo profondo, sino a 500m di profondità. L'utilizzo congiunto della sismica attiva e passiva ha permesso la definizione completa di un modello strutturale che è risultato in buon accordo con i precedenti studi considerati.

L'approccio deterministico ha infine permesso il calcolo di sismogrammi sintetici relativi ai più violenti terremoti che hanno interessato l'area, permettendo una realistica e ingegneristicamente fruibile valutazione della pericolosità sismica locale.

ABSTRACT

This work concerns the seismic hazard of a north Venice plain area, North Italy. The study of seismic local response is multidisciplinary. It involves geology, geophysics, seismology and engineering. The geological model of the area represent the starting point. Geophysical and Geotechnical engineering give the physics parametrization of rocks and sediments. Seismology defines the seismic sources, the waves media propagation and their interactions with subsoil geometry and properties. Engineers use ground motion properties to design seismic-resistance buildings.

A realistic seismic scenario of the studied area was the work's aim. We adopted a deterministic approach. This approach is able to compute the seismic motion of any earthquakes, even historical. This is really important for the area in exam, that was interested by strong historical earthquakes with no instrumental recording data. Initially we studied the historical seismicity of the area, and we focused on the strongest Earthquakes occurred. Then, an experimental seismic acquisition was developed, in order to define a realistic model.

The literature research involved geological studies, geophysical data, and well informations. Very importan were the past studies developed to hydrocarbon and thermal water exploitation (e.g. AGIP). In the studied area several gravimetric studies, seismic prospections and deep wells were done. All these data permitted a good knowledge of the subsoil geometry. No informations were available for seismic shear waves, that are fundamental parameters for seismic response analysis. Our experimental seismic acquisition was developed for this purpose.

The experimental researches had 3 main aims: record local earthquakes, confirm the bedrock geometry and shear waves measurements. For earthquakes recording we installed 2 station in continuous recording for 6 months. One station was in the northern part of the area, the other one in the southern part. We recorded 5 local earthquakes: 3 coming from the most seismogenic zone (N-NE), one coming from East and one coming from West. The records allowed to define the seismic response differences between north and south of the studied area.

To define the bedrock geometry a single station acquisition has been used.

The HVSR technique was used only to measure the subsoil fundamental period. We inferred, in undirected way, the deep of the main bedrock refractor. The Microtremors were used even for fundamental building period definition.

For shear waves measurements we focused on Rayleigh wave dispersion with Frequency Time Analysis method (FTAN, Levshin et al. 1972, 1992). We tested the new software XFTAN, developed by Dr. F. Vaccari and the research group of Prof. G.F. Panza of the University of Trieste. The Ftan method was first applied to earthquakes records, and it permitted the definition of bedrock shear waves. The shear waves dispersion of the sedimentary basin (500 m Thick) was defined with controlled source and passive seismic prospectings. For the controlled source experiments we used several sources: TNT, weight drop, seismic gun and heavy hummer. We defined accurately shear wave for the upper subsoil.

The passive prospecting, based on noise cross-correlation, is the most innovative aspect of the Thesis, and allowed to measure shear waves till 500m depth. The joint use of controlled source and passive seismic exploration gave the complete shear waves model we needed. The model is in good agreement with previous studies.

The deterministic approach afforded the synthetic seismograms for the strongest earthquakes that occurred in the area. The final results is a realistic definition of strong motion and seismic hazard, useful for engineering purpose.

INTRODUCTION

A seismic study is, necessarily, a multidisciplinary work. The evaluation of seismic hazard involves:

- a) the knowledge of the seismic sources and their mechanism, based on the historical and instrumental earthquake catalogue
- b) the seismic wave propagation study
- c) the knowledge of the geological structural model and the characterization of the subsoil
- d) the building seismic behaviours and their interactions with soil

Points a) and b) are competence of seismologists, point c) is competence of geologists and applied geophysicists, and point d) is competence of Engineers.

The main problems that occurs for seismologists are the doubt and the incompleteness of the historical catalogue and the lack of dense instrumental database. Infrequently geologists have an exact idea of deep structural model, and often the subsoil characterization has not the aim of the seismic behaviour determination. Engineer meet the difficulty of existing building seismic behaviour modelling, especially in case of ancient buildings.

The aim of this study is involve serious methodologies to answer the most of these questions for a Venice lowland coastal zone (Italy), even if this work is mainly directed to point c), and involve particularly applied geophysics.

First of all a bibliography research was necessary: we considered the historical earthquake catalogue to define a seismogenic model and we developed a research on the past deep explorations, to define a general geological model. Than, we developed an intense field-work with 2 main aims: the better definition of the geological model and the subsoil characterization, and the acquisition of local earthquakes. For the first purpose we based on the dispersion study of surface wave. We studied Rayleigh wave dispersion with Frequency Time Analysis method (Levshin et al 1972,1992; AA VV 1989). It revealed as a powerful technique to study complex signals, generated by controlled sources or inferred by noise. In fact, we developed active seismic explorations and many methodologies, even innovative, based on seismic noise measurements.

After a brief introduction of the area in exam, the Thesis explains the

instrumental experiments done on the field and the data elaborations. The experiments and elaborations described involve:

- Earthquakes recordings
- Controlled Source seismic surveys
- H/V analysis of seismic noise
- Analysis of building seismic behaviour
- The Time Cross Correlation of Seismic noise
- A Deterministic hazard scenario computation
- Results and Discussion

Earthquakes recordings permitted the instrumental prove that the Northern part of the studied Area exhibits a different seismic behaviour than the southern part, in case of events located in the most dangerous seismogenic zones. Active surveys involved the use of explosive and other impulsive sources to evaluate surface wave dispersion. After it, 1D shear waves models for the upper subsoil were inferred. A realistic seismic scenario needs shear waves definition even for deep structures. For this purpose we focused on the study of seismic noise, the only low cost source wherever available and able to reach deep structure informations. We performed the H/V technique (Kanai 1957, Nogoshi e Igarashi 1970), testing his application limits and his potentialities, specially in case of strong impedance contrast and simple subsoil geometry.

We studied especially Noise Cross Correlation Functions, and the possibility to recognize media Green function, evaluating the contribute of several noise sources, natural and anthropic.

For the building seismic behaviours we tried to consider 'in situ' experiments of existing buildings (Mucciarelli et al 2001), based on noise correlation between top and base of the buildings.

The final results allowed a deterministic seismic hazard study, so all these different but converging approaches permitted us a complete seismic study of the area in exam.

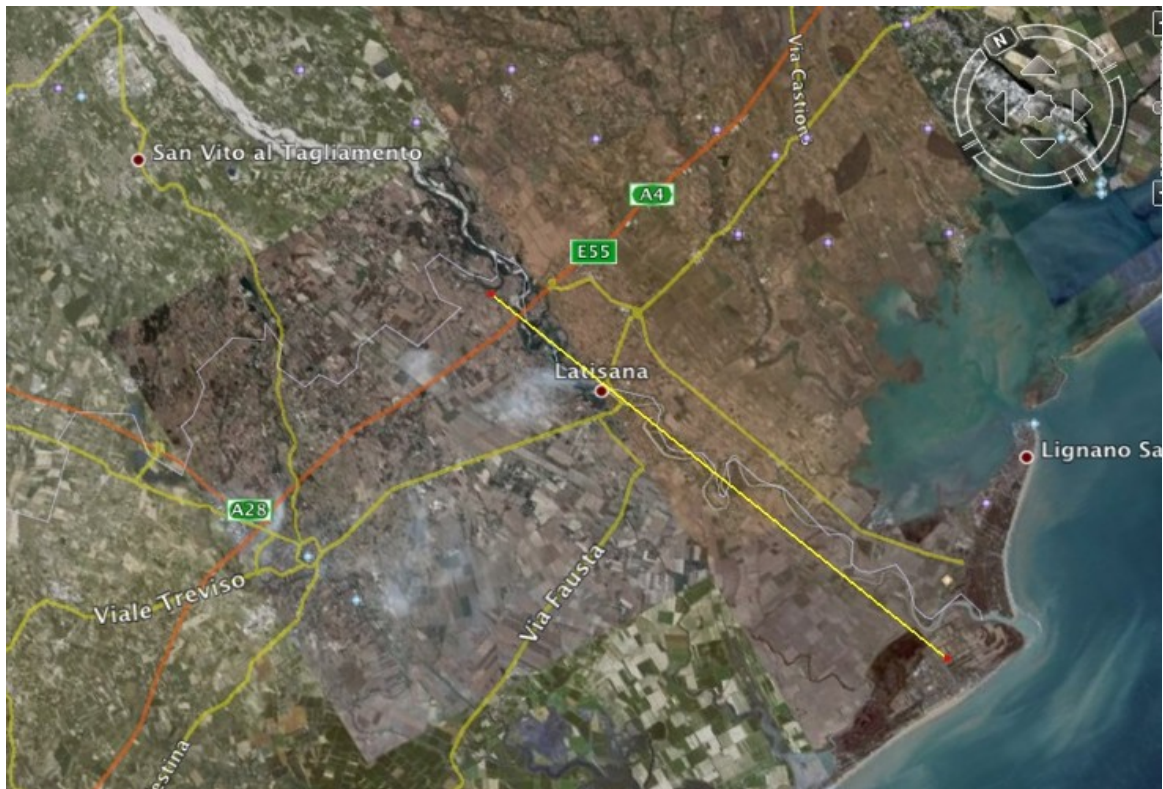
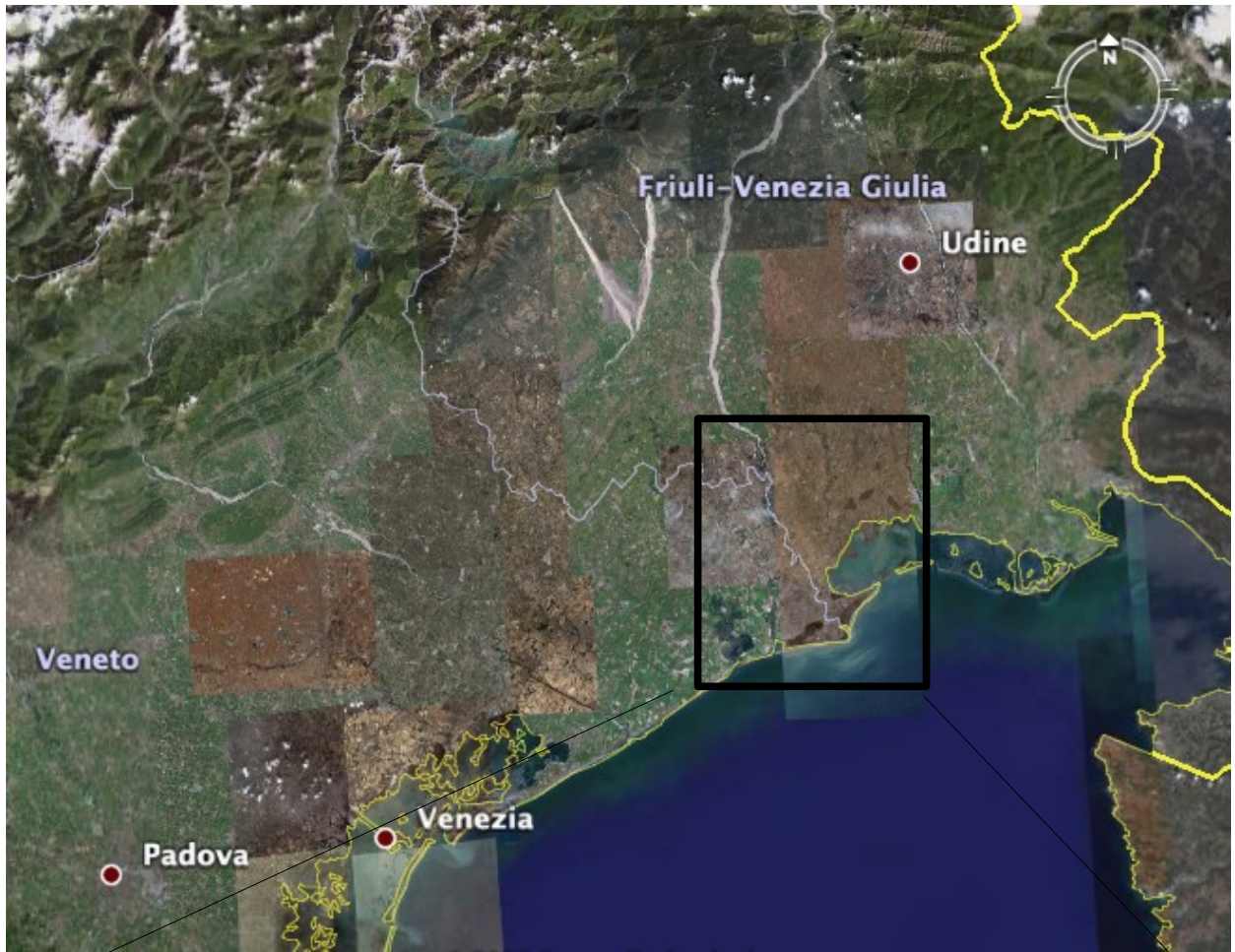
Chap. 1

Geological and Seismological Aspects

AREA IN EXAM

The area in exam is the most northerly part of the Venice lowland coast: San Michele al Tagliamento. We chose this Municipality because it represents a seismic-norm anomaly.

His territory, in fact, is stretched and developed on the North-South axis, from the Friuli Region limit to the Adriatic sea. This means a strong difference in the seismic behaviour inside the municipality limits, because the most strong earthquakes come from N-NE, and naturally involve the north zone of the Municipality stronger than the coastal one. The new Italian Seismic Zonation (2003) assigned for each Municipality a unique risk degree (from 1 to 4 with the decrement of risk), devolving to specific studies the inside limits characterization. Due to his lengthened territory, the 'S.Michele al Tagliamento' Municipality is classified as zone 3, and not 4 as the other near coastal zone. The study wants to fix as actual differences between the north and the south of this region are present, to define a seismic sub-zonation of the area.



Studied Area

1.1 Geological setting

From the geological point of view, the area in exam is located in the margin of the north Venetian lowland. This zone is modelled on a sedimentary bed of tertiary and quaternary deposits with clastic origin prevalent. Its thickness is about 500m.

The deep geological constitution of the area of interest is the north part of the Adria Plate. The great deformation phenomena of the Alp region are due to its movement toward north.

The Paleogeography of this zone is characterized, since the late Paleozoic, by epicontinental sea conditions. These conditions generated, in prevalent, carbonatic deposits of more than 6000m of thickness. This wide carbonatic platform was the forward-land between the Apenninic basin at West, and the Dinaric basin at East.

After an important extension and rifting phase, that interested the Alp region in the late Lias, the platform suffered an intensive fragmentation in blocks, due to the sedimentary rigidity. The collapse of some zones generated deep sea conditions, that stood till Cretaceous.

So we can define platform areas (Shelf), with low sea conditions, and deep sea conditions areas (Basins), that are connected each other with Slope.

Our area of interest is just located on the transition zone platform-basin, where are more accentuated the seismic instability conditions, with associated differential subsidence phenomena.

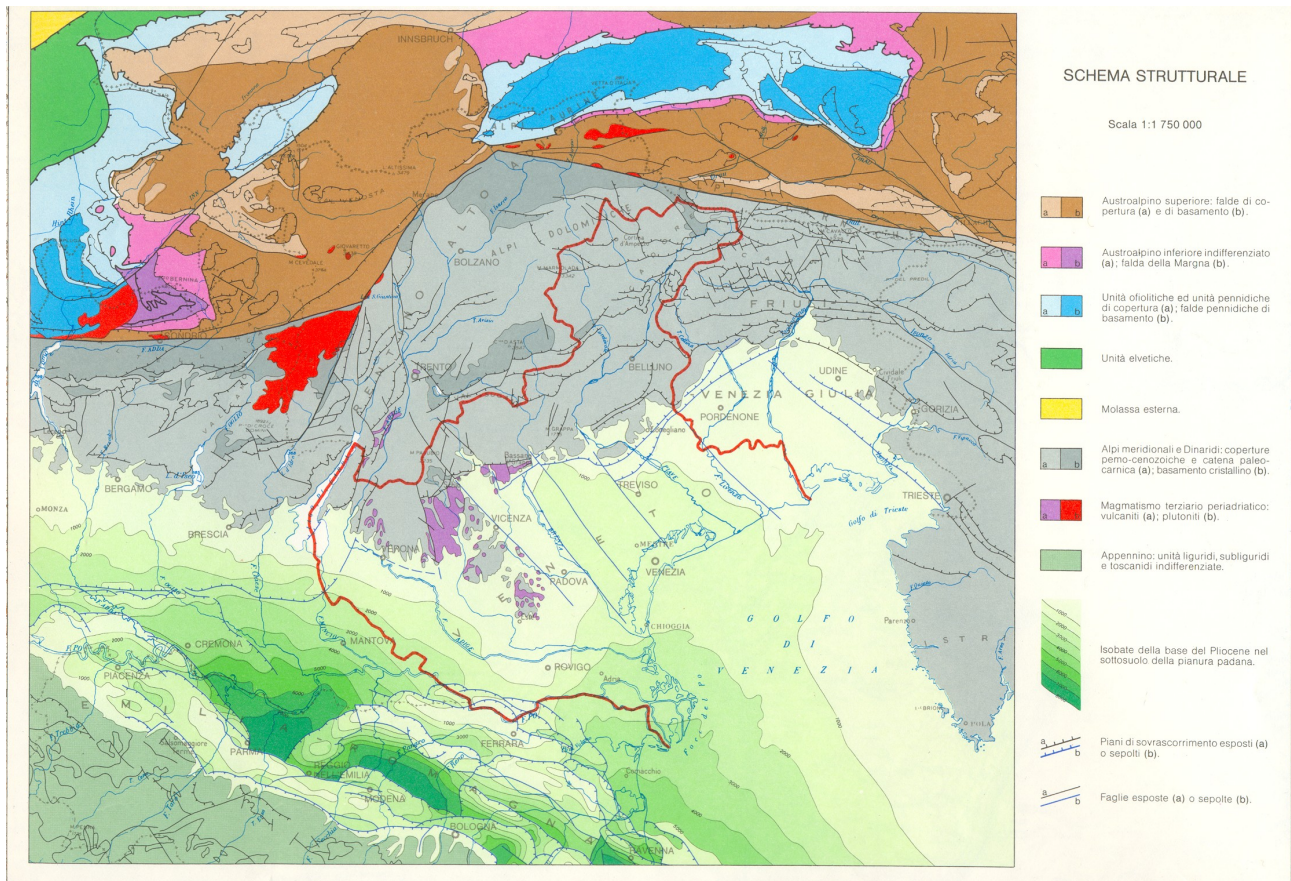


FIG 1 Structural Scheme of the Macro Region

We used many results of past geophysical prospecting works, for a more accurate knowledge of the geological conditions (e.g. Gravimetry, reflection seismic). Also deep borehole investigations for hydrocarbon research (AGIP) were obviously useful.

The gravity Bouguer (Fig.2) anomalies chart denotes a general gravity decrement from south toward north, due to the well known subsidence of the crystalline bedrock from the Adriatic sea to the Pre-Alps. The top of the basement is, in fact, estimated at 8 km depth on the Tagliamento mouth and at 11km near 'Gemona del Friuli'. A positive gravity anomaly exist in the coastal zone, from Caorle to Lignano, lengthened in the WSW-ENE ass. This remarks an important deep structural element. It is a Mesozoic ridge that develops on the margin of the Friuli platform. This zone of 'structural high' was intercepted by the Agip drilling 'Cesarolo 1' and 'Cavanella 1' (Fig.3).

The geological evolution, during Jurassic and Cretaceous, of the area in exam is characterized by the coexistence of the two ambience: Basin and Platform,

respectively in the North and in the South. These conditions started with the Lias rifting phase. In the upper Cretaceous the first Alp orogenic movements appear, due to the European plate – Adria Plate compression. This compression ruled the emersion of wide areas, the 'structural high' of Cesarolo included. In the SW of this structural unit continued the marine sedimentation while the terrigenous contribution took place. In the north of the Cesarolo ridge is more involved in the Alp orogenesis, as the Eocene Flysch attests.

The marine transgression reached the studied area, and the Cesarolo ridge especially, only in the Miocene. Epicontinental deposits cover the entire region overlapping the older, but with many sedimentation lacks. The Miocene sedimentation suffered the tectonic conditions too: due to the north toward immersion, the southern deposits thickness are significantly less than the northern one. This aspect can have an important role in the considered seismic hazard scenario. After a Pliocenic lack, all the area is interested by subsidence that favoured quaternary sedimentation, that was of marine, lagoon and continental nature. The upper subsoil is so characterized by clays, sand and gravel layers, for a thickness of 500m ca.

In conclusion the studied area is part of a 'structural high', busily crossed by two tectonic phenomena following the main regional directions: South- alpin and dinaric.

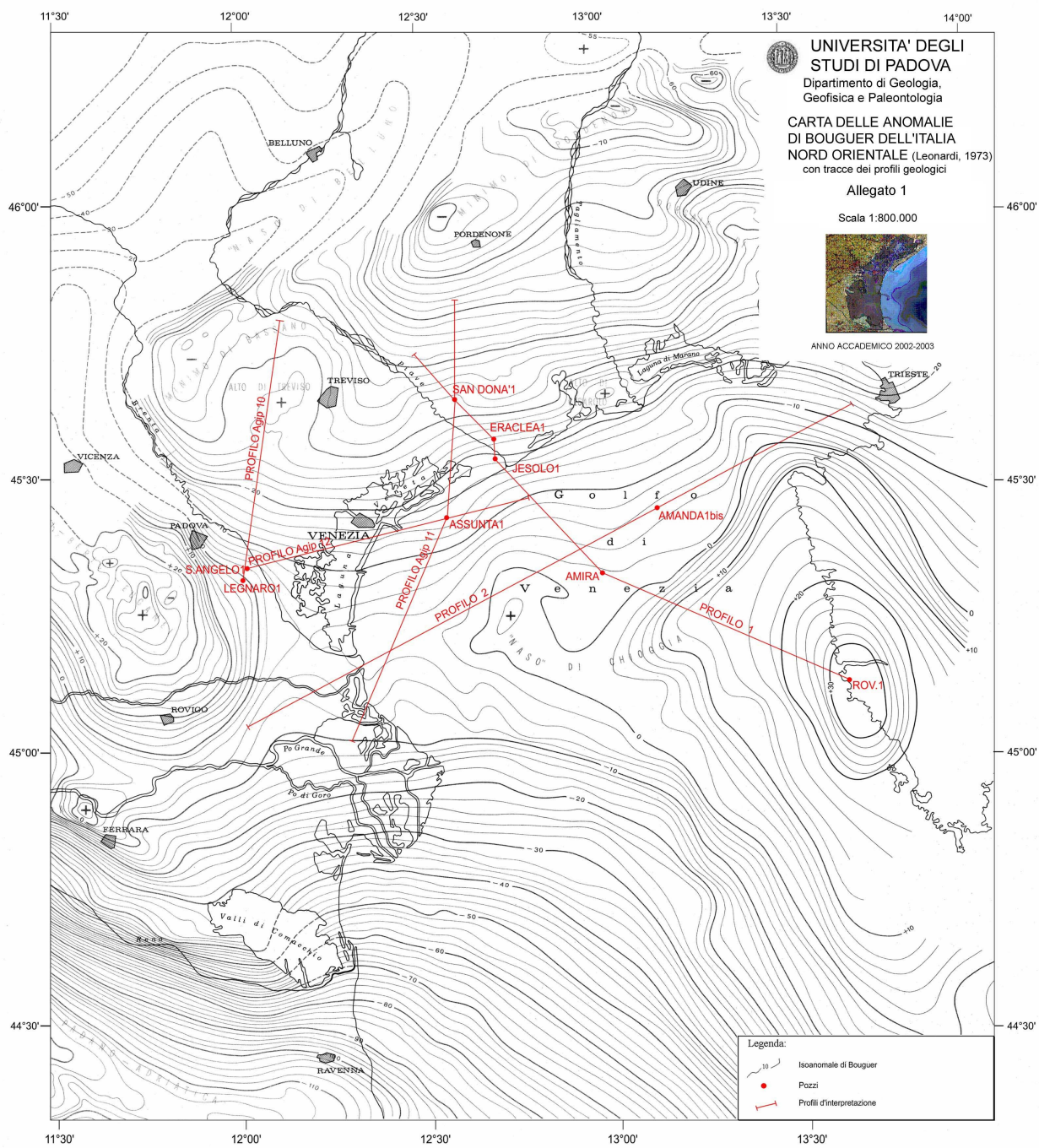


Fig.2 Bouguer Anomaly of the Macro region

1.2 Seismological Aspects of The Local Geology

From the seismological point of view, the studied area presents a general structural homogeneity of the upper subsoil. The fig.3 shows a seismic deep reconstruction, confirmed by drilling data and by the data acquired during our study (chap.5 and 6). We can affirm that the territory in exam is interested by a big quaternary sediments unit, with a thickness of 500m circa, over the more ancient Miocene/Pliocene bedrock.

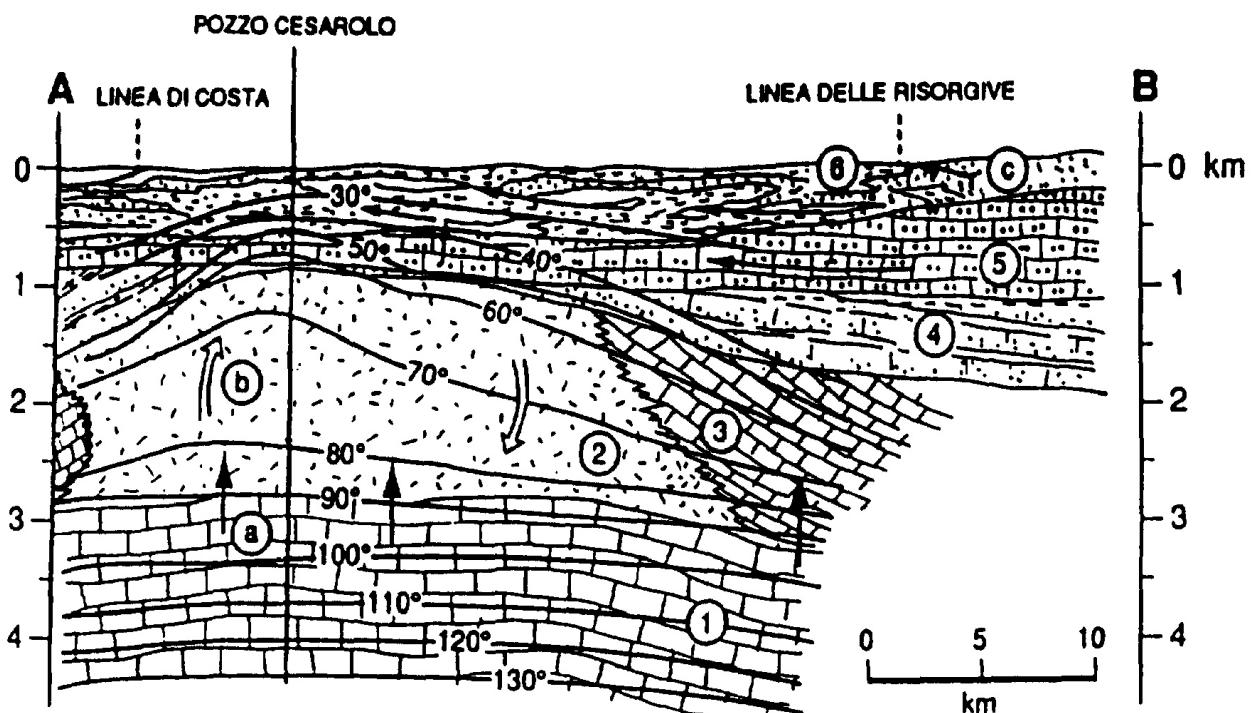


Fig.3 Structural Scheme of Studied Area 1) Dolomite, 2)-3)Limestones, 4)Flysh, 5)Sandstone, 6)Quaternary sediments

The presence of the 'High of Cesarolo' does not effect seismic local behaviour, due to his relevant depth. The upper subsoil instead is homogeneous that is underlined by the poor altimetric variation (few meters between North and South) and the absence of significant high or slope on surface (considering the well-known important influence of topography variations on seismic effects , e.g. Bard 1997).

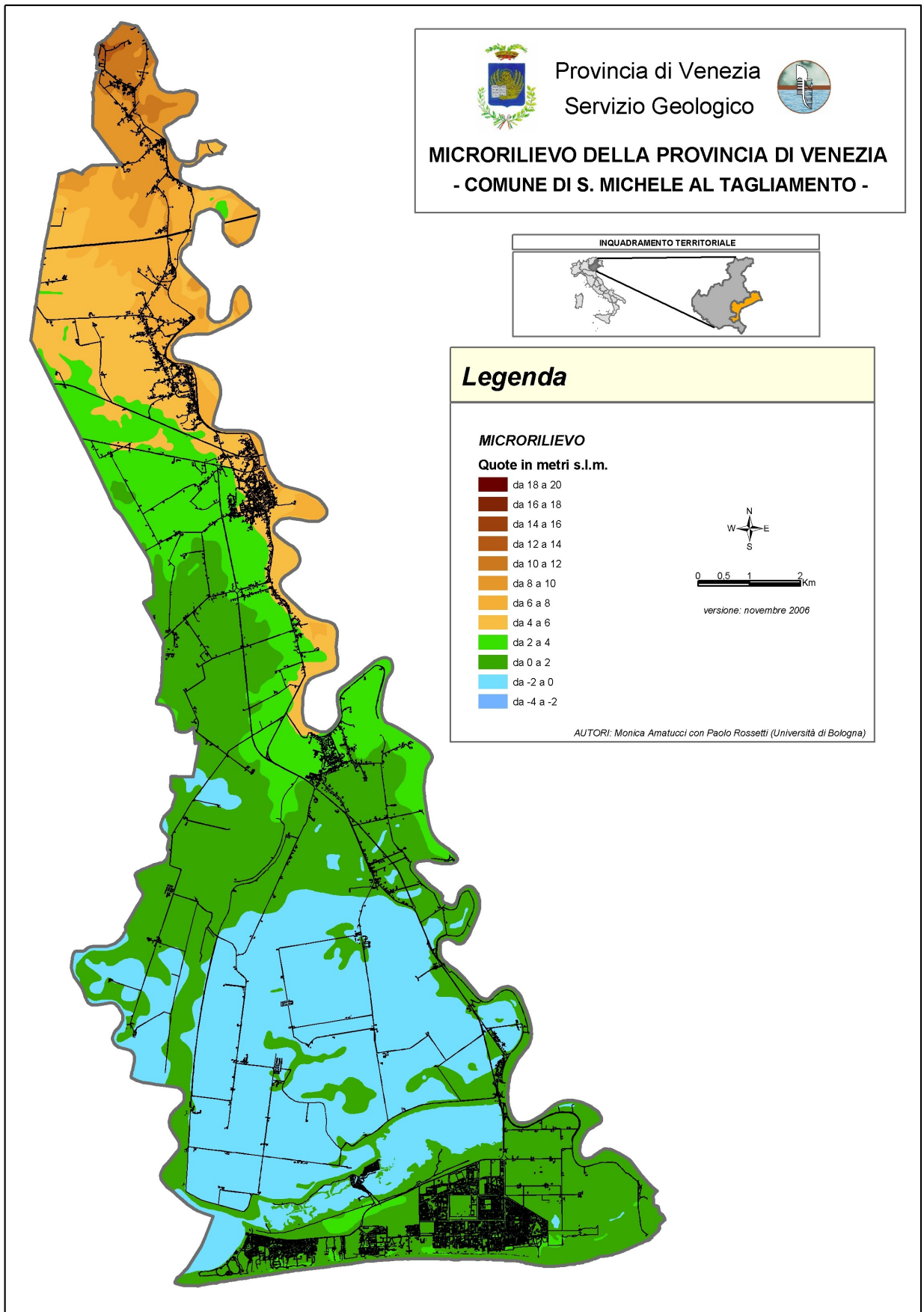


Fig.4 Micro- altimetric map

The morphological differences are only present on the coastal marine deposit while, for the rest of the territory, is interested by terrigenous deposits linked to the Tagliamento river digress. If we consider the strictly point of view of the seismic local response linked to topographical effects, these deposits are not considered inhomogeneous, cause their poor altitude. These consideration is supported by theoretical simulation.

Let's consider the upper subsoil conditions. For this study we wanted to be consistent with the seismic soil classification of the Italian seismic law, that assumes the same parameters of Eurocode 8, categorizing the subsoil with the shear waves of the first 30 meters. The territory examined present 2 different soils (classified as C and D type using Ec8- chap 4). This underlines the poor reliability of the official Italian Hazard Map (law 3519), that consider all the national territory as soil A (rock). Obviously are expected many differences between the real seismic soil behaviour and the acceleration predicted by that law map, that can overestimated (due to the weak attenuation of rock) or underestimate the soil movement.

Seismic strong events never occurred in the studied area. Even for the seismic hazard national map, the Venice coastline isn't considered as a seismogenic zone (seismogenic Zonation ZS9 INGV) and is considered menaced only from far sources (Fig.5).

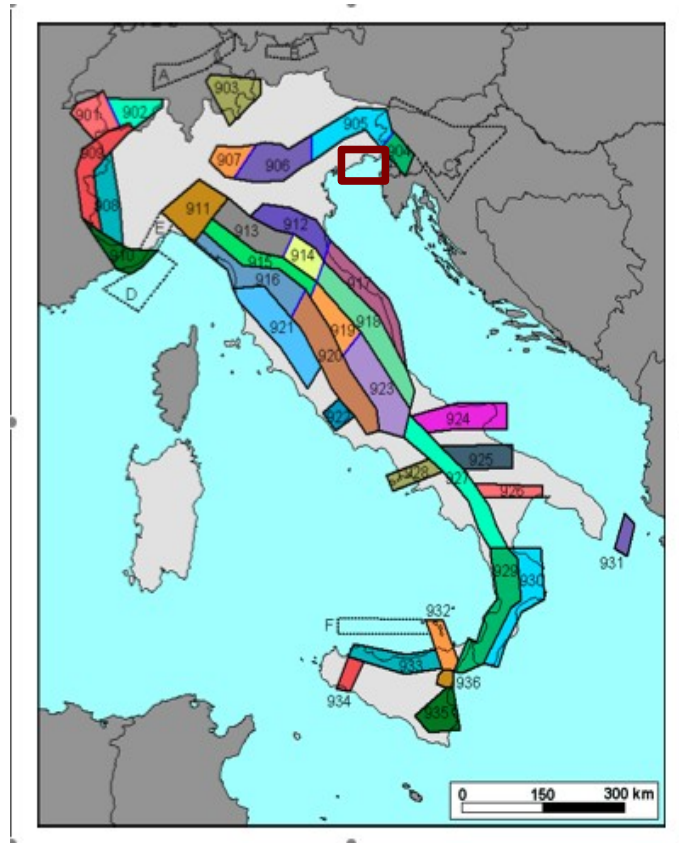


Fig.5 seismogenic zones for Italy, From ZS9 INGV. In red square the Studied Area.

1.3 An Overview on the National Seismic Classification of the Area

The recent Italian Seismic Hazard National Map (law 3519), attributes to the studied territory two values of the maximum ground acceleration attempted. To the major part of the territory an acceleration between 0.05 and 0.1g is assumed. Only for the northern part of the territory the estimated ground acceleration is between 0.1 and 1.25g.

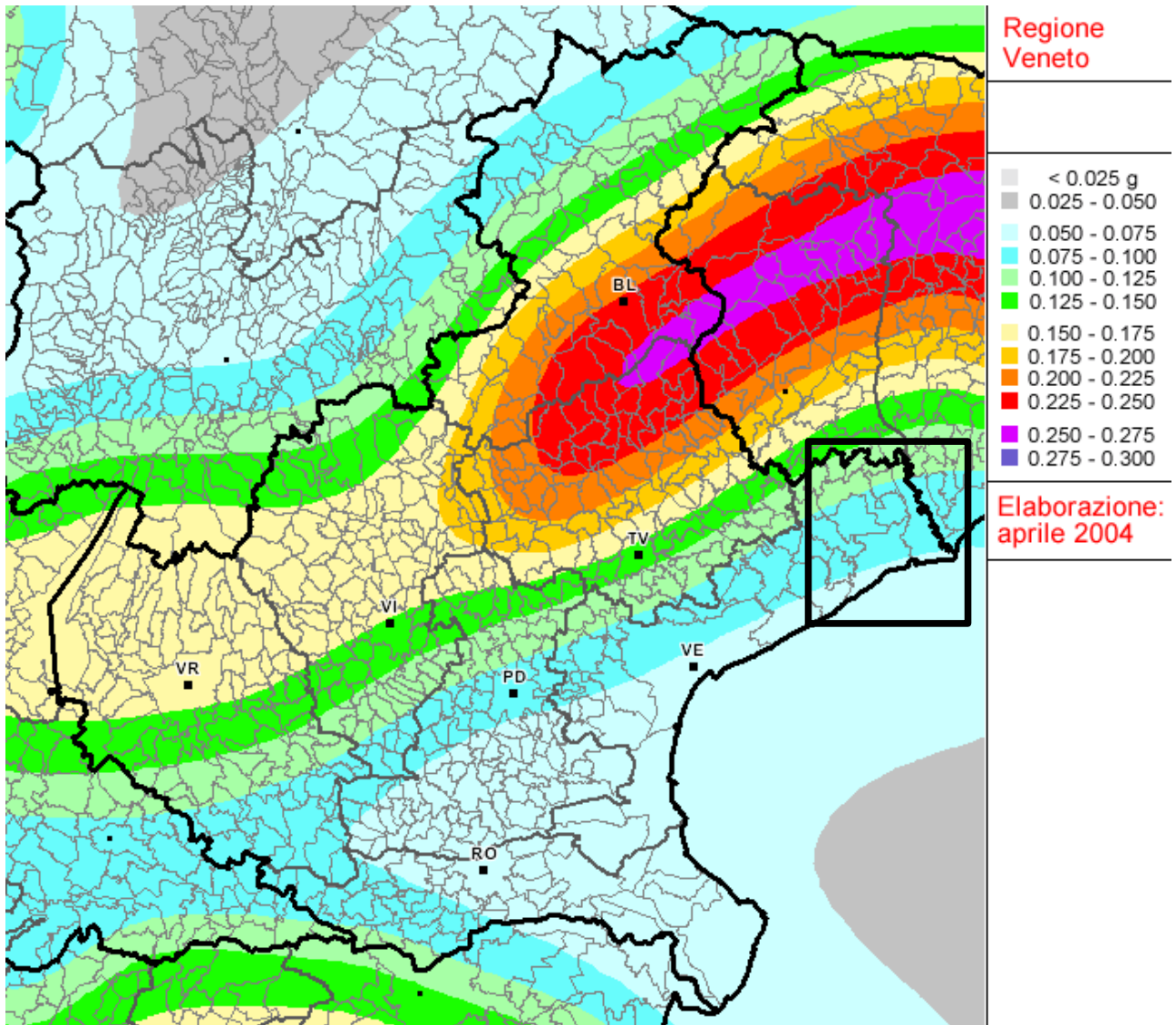


Fig.6 Hazard map for the Macro Region from Italian Seismic Hazard Map. Maximum ground acceleration (exceeding 10% in 50 years, referred to bedrock condition). In square the studied area.

As shown in figure N.6, the most critical acceleration interest the Friuli area, with acceleration over 0.25 g . The Hazard map, developed by the Italian Institute of Geophysics and Volcanology, is based on the strong Italian earthquakes catalogue (e.g. CPTI04), and on the INGV seismogenic zonation (ZS9), which considers the epicentral areas. The epicentral areas of our interest are 904, 905 and 906 zones (Fig.5).

The Fig.7 shows the recent earthquakes that afflicts the area in exam. The pre- alpine arc, from the Veneto to Slovenia regions, is the most dangerous seismic zone of the region, even if low seismicity is widely diffused (lowlands, Trieste gulf and Istria peninsula).

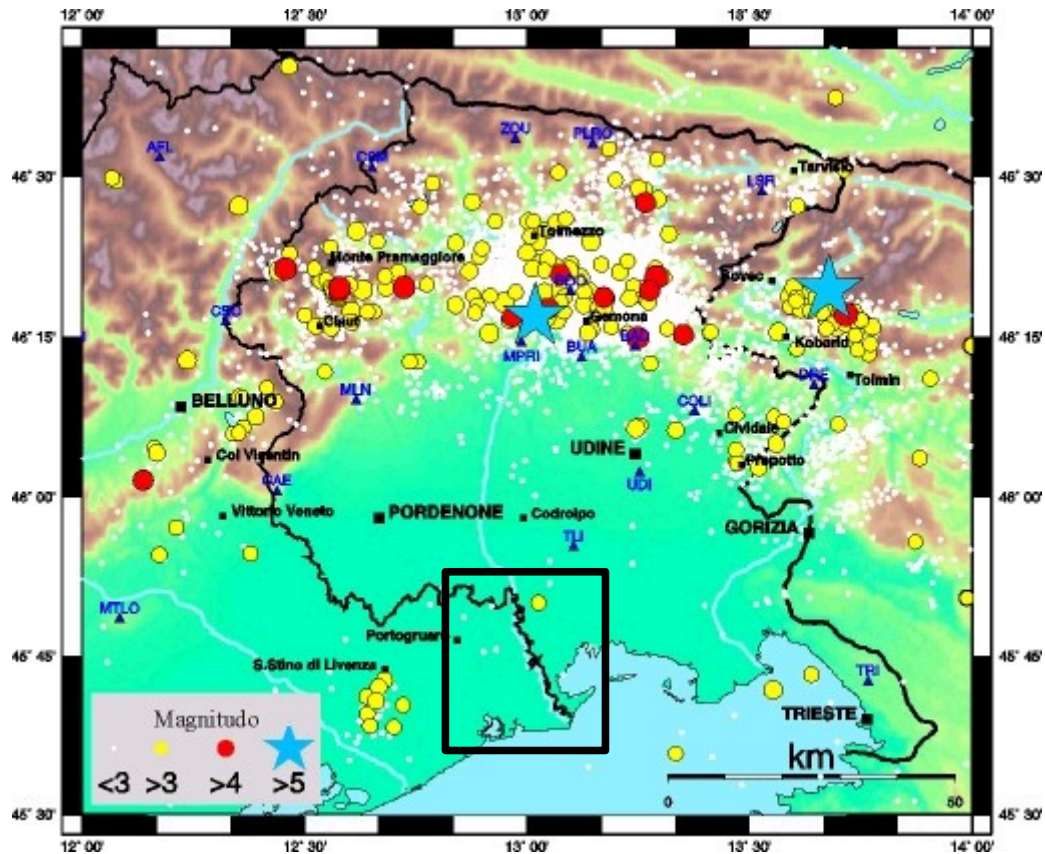


Fig.7 Recent Seismicity of the macro Region. In square the studied area.

The Venetian seaside is only quite involved by the alpine seismicity (Fig.8). For example one of the most critical earthquake occurred, the Friuli 1976 event, did not cause serious damages at the area in exam.

Following the criteria that lead to the Seismic Hazard Map, the earthquakes of the pre- alpine arc are the most dangerous events attempted. A local seismic hazard estimation must focus on the event occurred from that area.

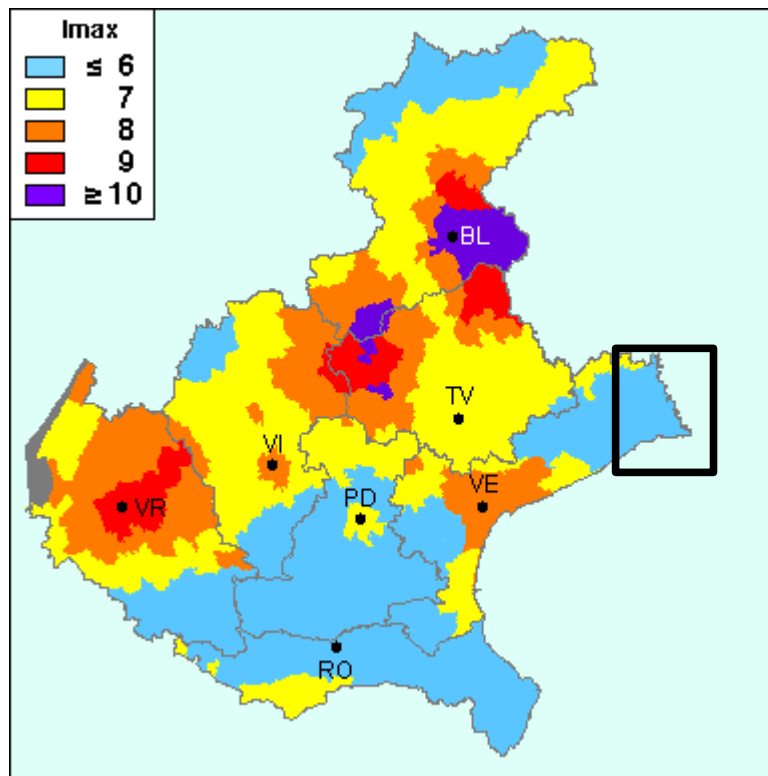


Fig.8 Macroseismic Intensity for the Macro Region. In square the studied area.

Chap.2

Experimental Activities

Local Earthquakes Recordings

One of the study purposes was to verify different seismic behaviour between the North and the South parts of the Area.

For this reason our attention was focused on two sites: 'Malafesta', at the northern part of the studied area, and 'Bibione', in the southern and coastal zone of the area (Fig.10).

As explained in the introduction, the national seismic hazard map considers that the most dangerous events, for our studied site, come from the pre-alp region (from N-NE). For this scenario an attenuation of seismic energy from North to South (than from Malafesta to Bibione) is foreseen. Our intention was to demonstrate this loss of energy in an experimental way.

Two seismic stations (with the characteristics well displayed after) were installed on the 2 sites. The aim was to record seismic events coming from the most dangerous zone (N-NE), but also coming from other seismogenic zones (W and E). Taking in consideration this 'lateral' events was necessary to comprehend the possibility of specific site amplification effects. Lateral earthquakes, in fact, interest the 2 stations with the same (more or less) epicentral distance. It must be said that the geological homogeneity described above, does not theoretically permit strange local effects for the two sites. Our study wanted however to consider this possibility with instruments on field.

We thought that, due to the local seismicity, we should recorded the events searched in a couple of months. The summer of 2006 was, instead, a silent period and we had to extend our registration time for more than 6 months, with many obvious logistic problems (energy supply, download organization etc.).

We recorded 5 local earthquakes, 3 from the dangerous N-NE seismogenic zone and 2 from lateral direction, useful for project purposes.

Localization of the Instruments:

<u>Malafesta:</u>
from 3/6 to 6/10 c/o “campo sportivo Polisportiva Malafesta” near the ancient school
4549.6967 °Lat N
01257.7049 °Long E
Satellites seen : 4
from 6/10 to 9/15 c/o non in used building in via Isonzo
4549.5925 °Lat N
01258.1129 °Long E
Satellites seen : 4
<u>Bibione:</u>
from 3/6 to 9/15 c/o Bibione cemetery
4539.4050 °Lat N
01304.4624 °Long E
Satellites seen : 4

Notes: The first installation of Malafesta was leaved in June because too much noising (the most probably cause are the frequent use of the soccer playground). The building of 'via Isonzo' and the Bibione cemetery were instead good silent locations.

We installed 2 seismic receivers “Tromino” (Micromed). Technical specifications of the Instruments used (from constructor) are explained in pg 29.

2.1 Technical Receivers data

TROMINO is an instrument designed for seismic tremor measurements. Its miniaturization (10 x 14 x 8 height cm) and lightweight (1.1 kg), its low energy consumption, the total absence of external cables, and the high-resolution of its digital electronics make it an almost pockets instrument.

The device is endowed with 3 analog channels connected to 3 orthogonal high resolution electrodynamic velocimeters, plus 1 channel for GPS signals. Earth motion is amplified, converted into digital form, organized, transferred to a Compact Flash card and then to the PC. The storage, analysis and the review of the data are performed through 'Grilla' (proprietary software).

Setting TROMINO into operation is due s to its LCD which provides guidance in the parameters choice such as the recording mode, the acquisition time, the total available memory and the internal electronic noise monitoring. The display allows also viewing acquired traces in real time and in review.

It is powered by 2 internal AA batteries: useful to acquire high-quality signals even in electromagnetically polluted environments. The consumption of 75 mW (GPS inactive) ensures more or less 80 h continuous measurement. Memory storage limits are only those imposed by Flash card technology: our instruments had a 1 Gb Card (which means about 20 days of continuous acquisition on 3 channels at 128 Hz sampling frequency). A data compression system, safe against data loss, allowing to extend the recording duration by approximately 30%.

The GPS synchronization and marker allow TROMINO to be used in array or network configuration.

SPECIFIC DATA (from Manufacturer)

Manufacturer: Micromed s.r.l.
Classification: CISPR 11 - EN 55011 (Industrial, scientific and medical (ISM) radio- frequency equipment - Radio disturbance characteristics - Limits and methods of measurement), Group 1 Class B. Conformity to standards: EN 55011, IEC 61000- 4- 2, IEC 61000- 4- 4, IEC 61000- 4- 3.
Power supply 2 x 1.5 VDC AA, alkaline battery Internal voltage +3.3 V, +3.6 V for the analog section Power consumption 75 mW (GPS inactive), 450 mW (GPS active) Battery duration 80 h continuous, GPS inactive
Number of channels 3 + 1 analog
Amplifiers all channels with differential inputs
Noise < 0.5 μ V r.m.s. @128Hz sampling
Sampling frequency 16384 Hz per channel
Oversampling frequency 32x, 64x, 128x
A/D resolution 24 bit equivalent
Max analog input 51.2 μ V (781 nV/digit)
Clock internal , permanent with date and alarm, can be visualized also during the acquisition
GPS 12 channels with time- marker (precision 1 ms)
Level spirit, horizontal high precision, sensitivity 5' arc (0.083°)
Connections type B, USB port
Data recording internal memory 1 Gb
Dimension and weight 10 x 14 x 7.7 (height) cm 1.1 kg aluminum case
Ground coupling spikes or rheological cushion
Operating environmental conditions temperature - 10 / +70°C, humidity 0- 90% without condensation
Impermeability IP protection index 65 (dust proof, splash proof)
Sensors 3 orthogonal electrodynamic velocimeters with ~ 1 Hz proper eigen- frequencies, self- locking when not in acquisition. Grilla software automatically corrects for sensors frequency response
Sensor frequency range 0.1 - 256 Hz.

Example of Noise maximum and minimum of the Earth (J. Peterson, Observations and modelling of background seismic noise, Open- file report 93- 322, USGS, 1993) is shown in Figure 9.

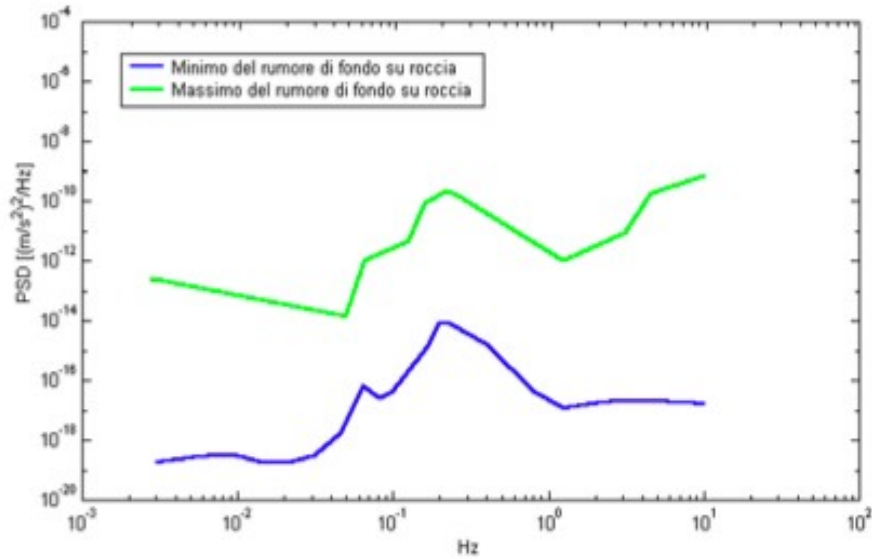


Fig.9 Standard seismic noise models of the Earth, Maximum and Minimum, Power Spectra in acceleration, vertical component.

Installation

The stations were installed with the best soil coupling. They leaned on cement floor in both locations. Levelling was done with 3 micrometrical screws orientating one of the 3 axes with the magnetic North. No structural changes involved the host location. A continuous recording at 128 Hz sampling was performed.

GPS

All the acquisitions were done with GPS continuous measurements, for the correct synchronous UTC time between the stations. The internal clock of the instruments is, in fact, obviously sensible to temperature, humidity, and energy changes. A correct correlation within the station had to be based on UTC time from satellites. For this purpose we paid attention to the antenna installation, that must have satellite visibility with no interruption.

In Malafesta the antenna (that has a magnetic base) was installed on an exterior railing, at Bibione directly on the roof of the hosting building.

Energy Supply

The receiver power supply is higher than the declared (450 mW with active GPS). It was necessary to charge the battery supply many times, with an accurate voltage monitoring. The internal battery of the instruments has allowed the acquisition during these re-charge operations.

Data Download

All the data was downloaded with Grilla software (Micromed). The download was done every 15-20 days, always large under the memory limits. 2 weeks of data decompressed are about 1.5Gb and the time of downloading was about 2 hours for an instrument. The total amount of the data recorded surpasses the 30Gb. An external memory device was used for safety.

2.2 Results

Limit the study to the energy attenuation, linked to the distance from epicentres, does not mean obviously evaluate site effects. Many historical cases, e.g. Mexico city (1986) or Messina (1906), demonstrated, even at large distance from the event, that geological local site conditions could mean great motion amplification. In many cases the greatest damages occurred far from epicentre than near. For this reasons, the aim of this studio was not only to record events coming from the Alp region (the most dangerous as explained before) but also coming from Veneto lowlands and Slovenia. Strong site effects influence was extremely linked to the direction of the incoming energy, so the record period was extend to 6 months to record several events coming for difference sources.

We recorded 5 useful earthquakes for our purposes, with magnitude (ML) between 2.4 and 3.4. Other event occurred during the recordings period, but with too low magnitude or too far to be distinguished from noise.

We recorded 3 earthquakes coming from N-NE, the most dangerous seismogenic area for our zone, and 2 earthquakes coming from central Veneto lowland and from Slovenia respectively (almost equidistant for the two stations fig.10).

Earthquakes Data:

<u>Gemona Earthquake</u>
Date and Time 11/08/2006; 03.35.56
Epicentre 46°19'18'' – 13°08'5'' N E
Localisation : Gemona del Friuli
Magnitude 3.0 Richter
Distance from Malafesta Station ≈ 52.5 Km
Distance from Bibione Station ≈ 71.2 Km

<u>Arta Earthquake</u>
Date and time 25/07/2006; 03.38.36
Epicentro 46°27'07'' – 13°03'46'' N E
Localisation: Tolmezzo
Magnitude 2.9 Richter
Distance from Malafesta Station ≈ 70 Km
Distance from Bibione Station ≈ 90 Km

<u>Clautana Earthquake</u>
Date and Time 23/07/2006; 14.48.15
Epicentre 46°19'10'' – 12°34'59'' N E
Localisation: Claut
Magnitude 2.4 Richter
Distance from Malafesta Station ≈ 58.7 Km
Distance from Bibione Station ≈ 81.2 Km

<u>Galliera Earthquake</u>
Date and Time 20/07/2006; 22.47.56
Epicentre 45.67 11.84 N E
Localisation: Galliera Veneta
Magnitude 2.9 Richter
Distance from Malafesta Station ≈ 93.75 Km
Distance from Bibione Station ≈ 98.7 Km

<u>Stregna Earthquake</u>
Date and Time 23/04/2006; 18.21.37
Epicentre 46°05'16'' - 13°36'19'' N E
Localisation: Stregna, Slovenia Border
Magnitude 3.4 Richter
Distance from Malafesta Station ≈ 55 Km
Distance from Bibione Station ≈ 57.5 Km

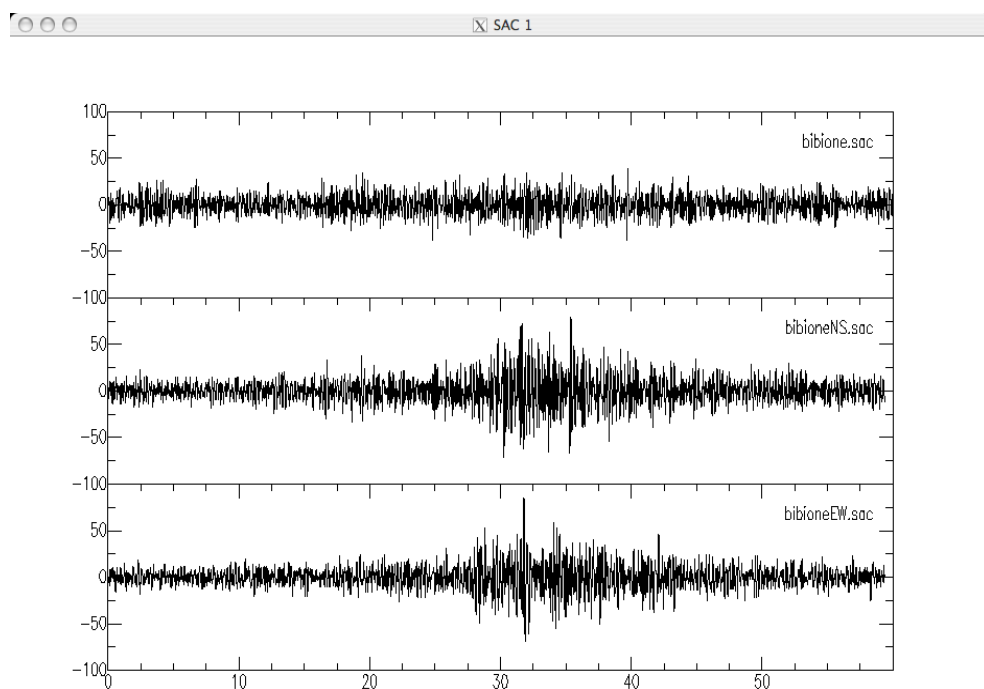
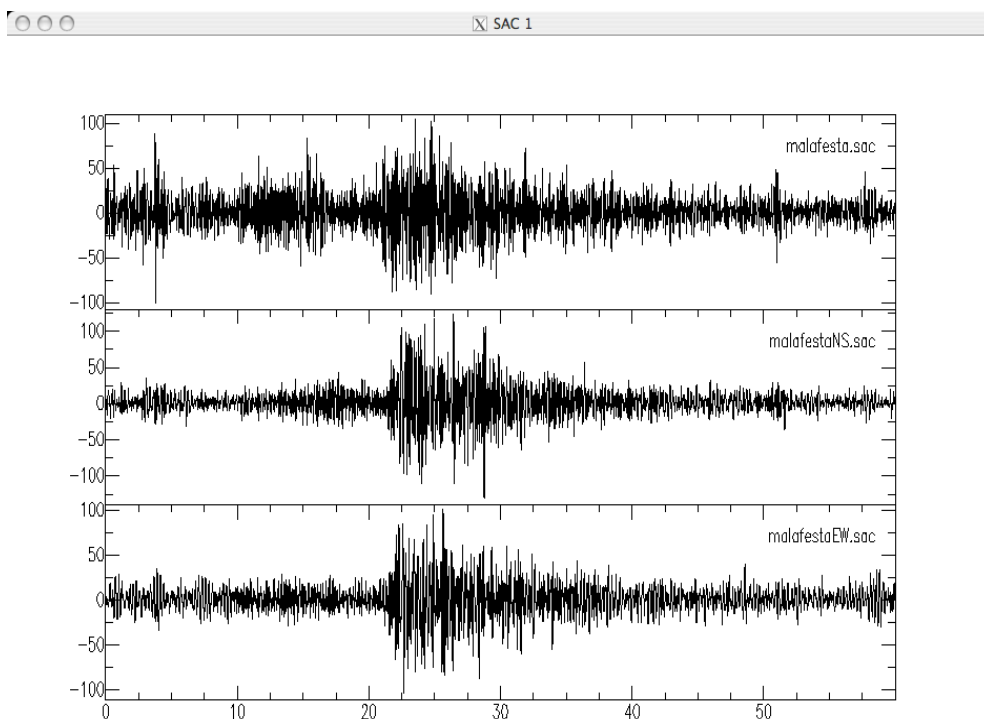


Fig.10 Earthquakes recorded. Yellows Triangle are the installed stations. In red star earthquakes coming from dangerous seismogenic zones, in blue star earthquakes coming from lateral directions.

Figures below shows the rough recorded seismograms of the 3 events coming from the most dangerous area (Fig.7), the Gemona, the Arta and the Clautana Earthquakes. The 3 components of motion for the both station Malafesta and Bibione are showed.

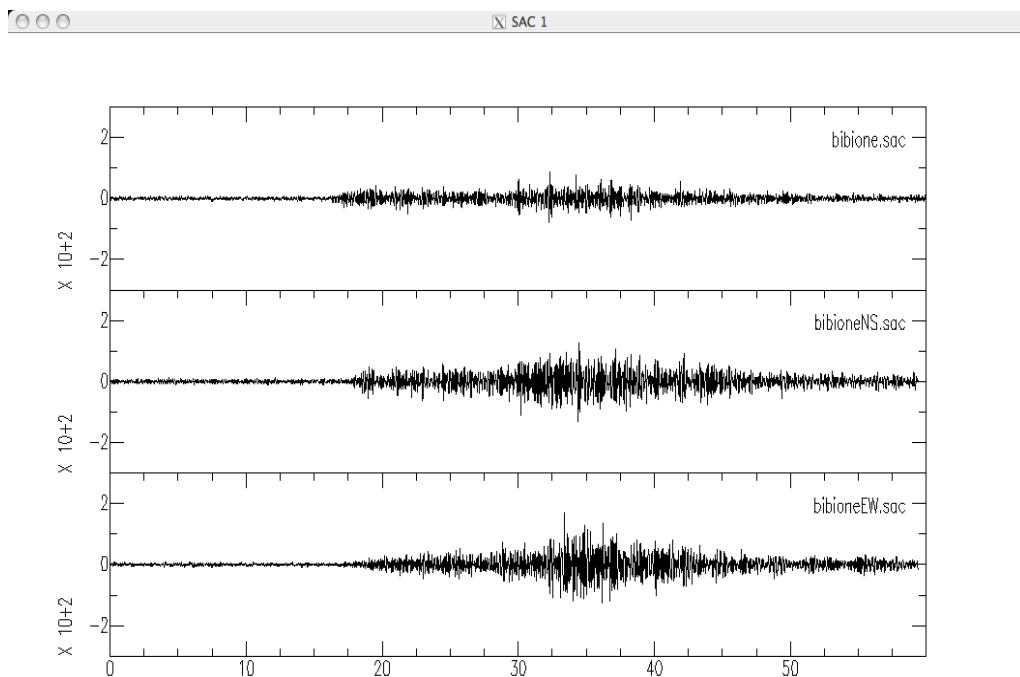
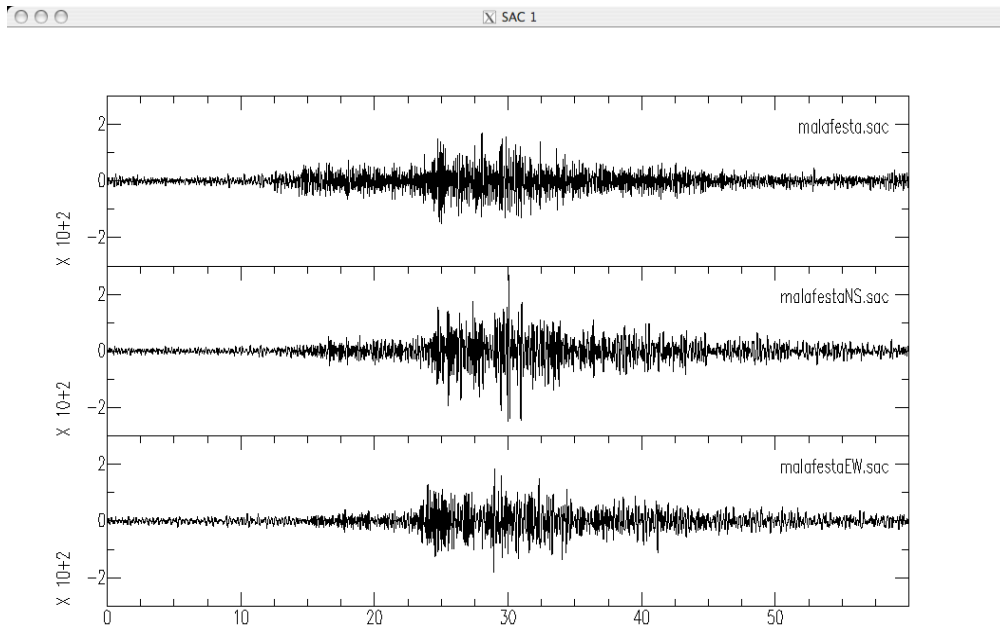
Gemona Earthquake

Malafesta (top) and Bibione (bottom) stations
vertical, radial and transversal components
same amplitude axes, time in seconds



Arta Earthquake

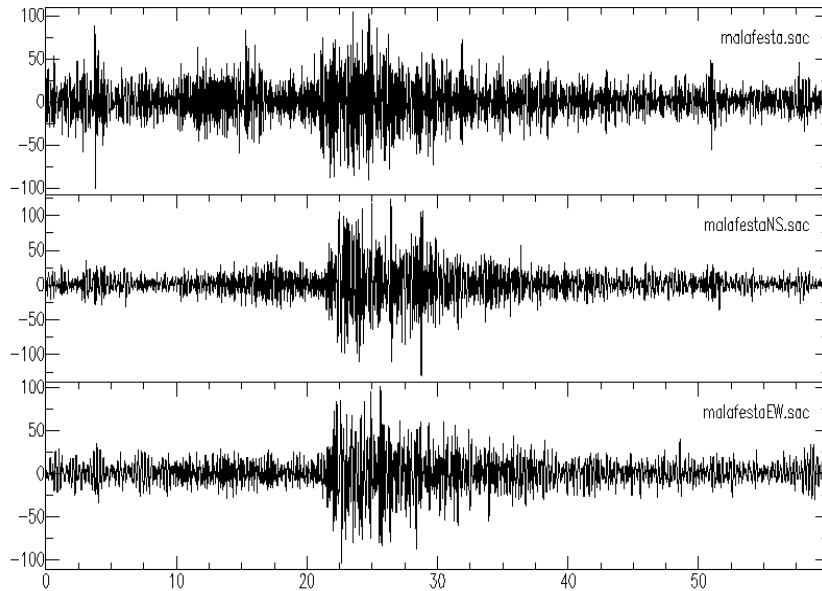
Malafesta (top) and Bibione (bottom) stations
vertical, radial and transversal components
same amplitude axes, time in seconds



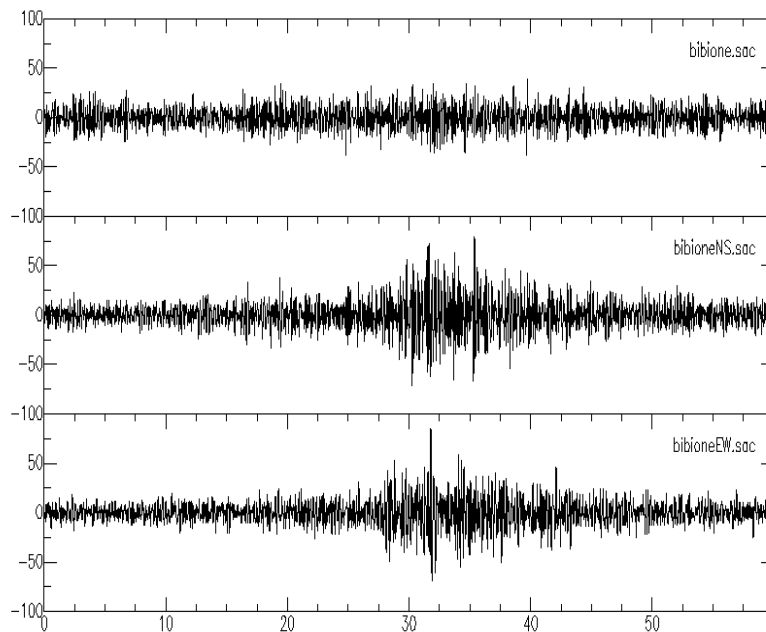
Clautana Earthquake

Malafesta (top) and Bibione (bottom) stations
vertical, radial and transversal components
same amplitude axes, time in seconds

SAC 1



SAC 1



The Earthquakes coming from the most dangerous seismogenic zone are clearly attenuated at Bibione Station. The obvious difference is linked to the distance attenuation. Fig.11 shows the comparison between the vertical component recorded at Malafesta station and at Bibione station for the Gemona earthquakes. The attenuation, linked to the 25 km distance between stations, is clearly visible.

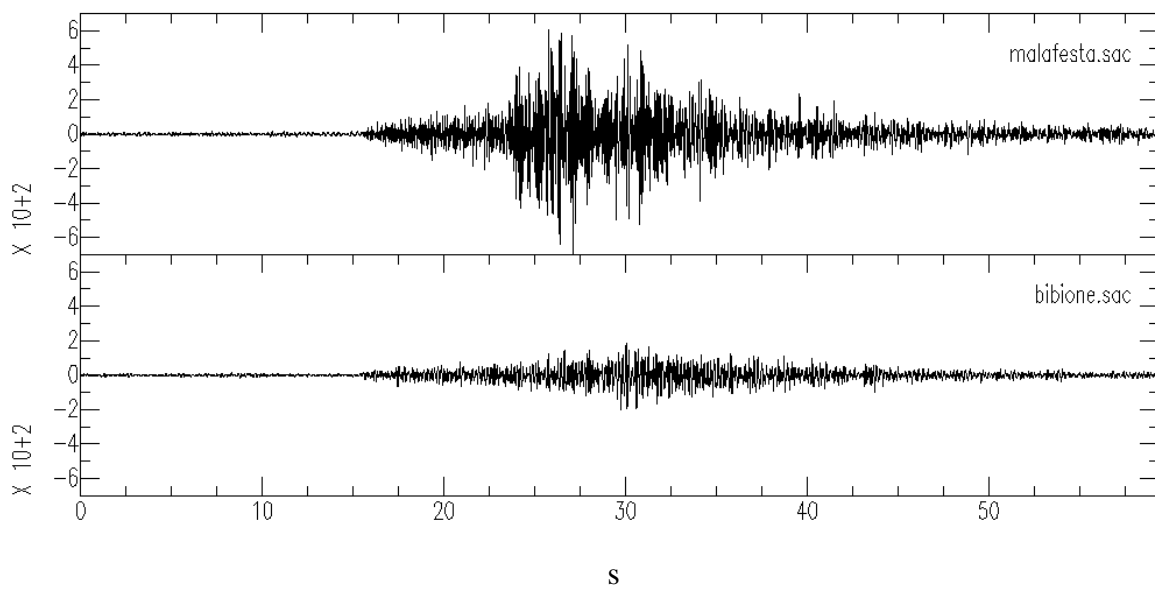
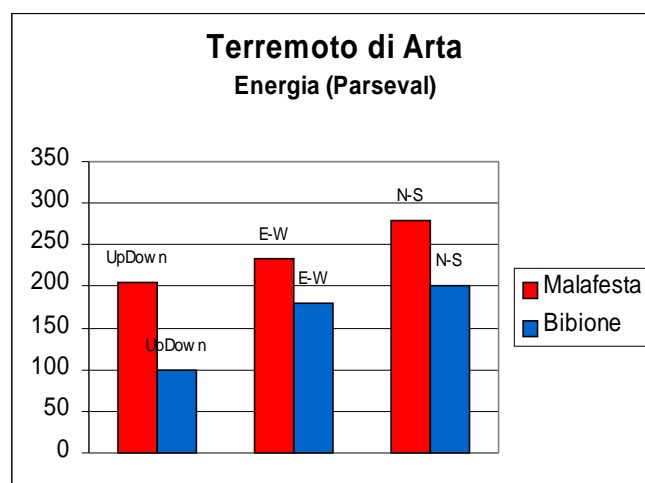
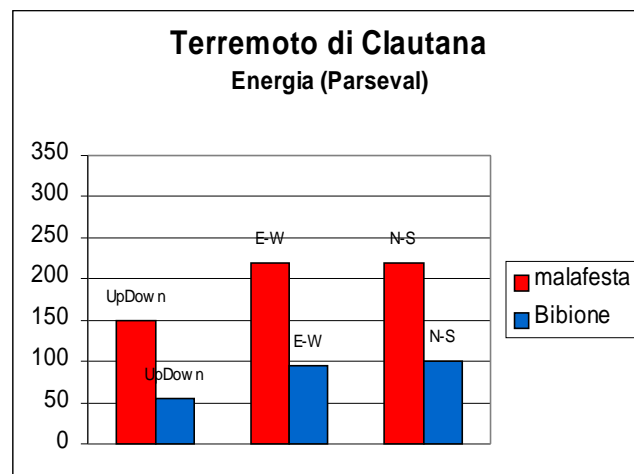
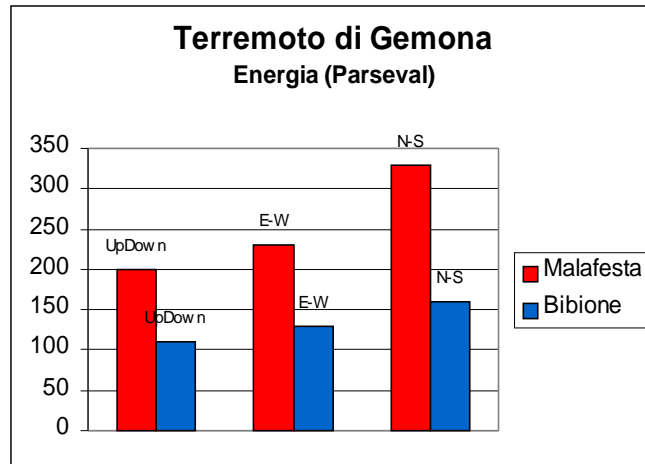


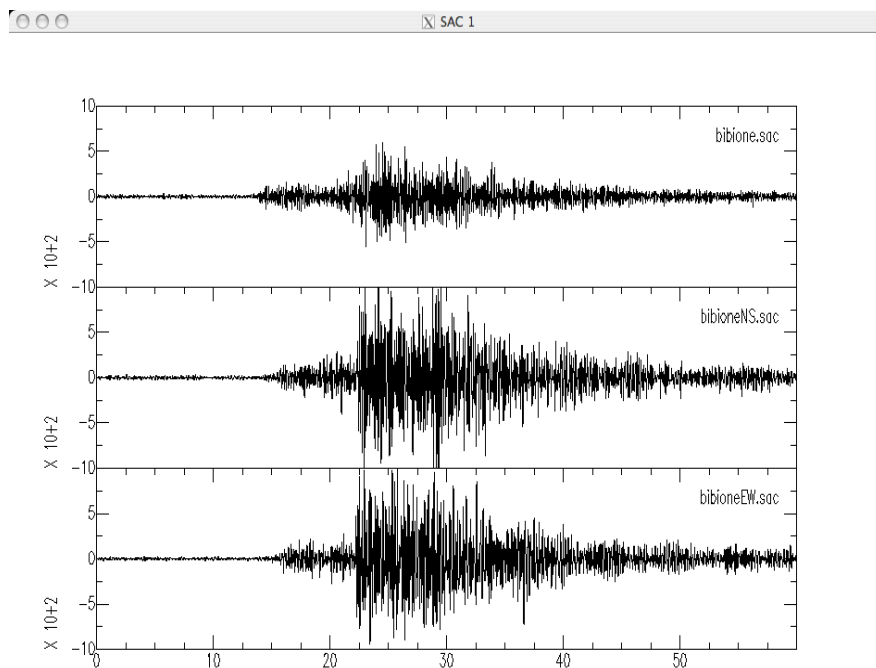
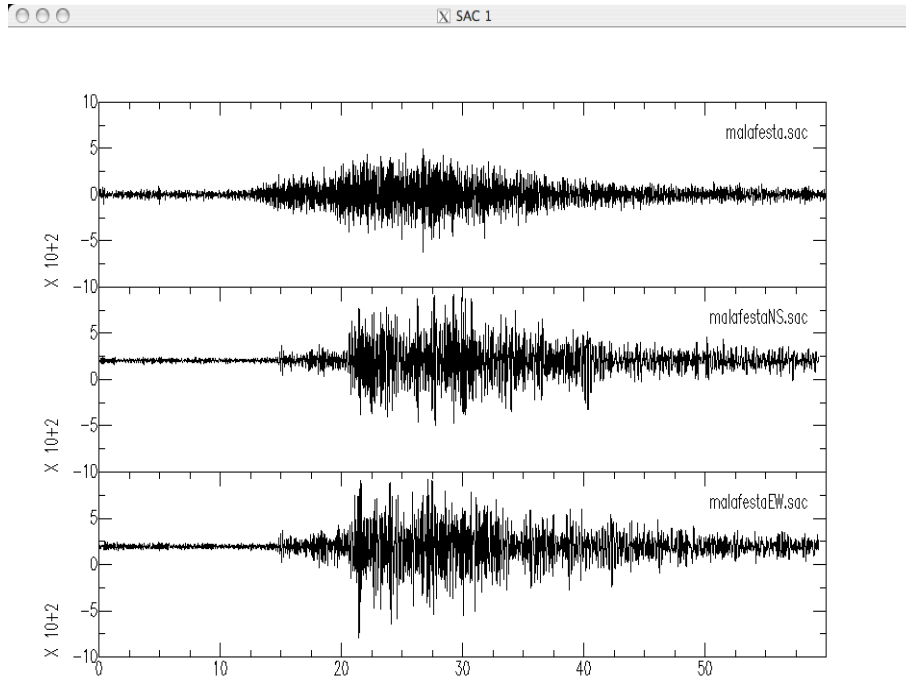
Fig.11 .Vertical component of the Gemona Earthquake recorded at Malafesta station (top) and Bibione station (bottom). Time in seconds.

The difference between the 2 stations is clear even in term of Parseval energy, as shown in graphs below (energy for the 3 component of the earthquakes coming from N-NE). Figures in pages 40-41 show the seismogram of the event coming laterally from E and W (Galliera Veneta and Stregna Earthquakes)



Stregna Earthquake

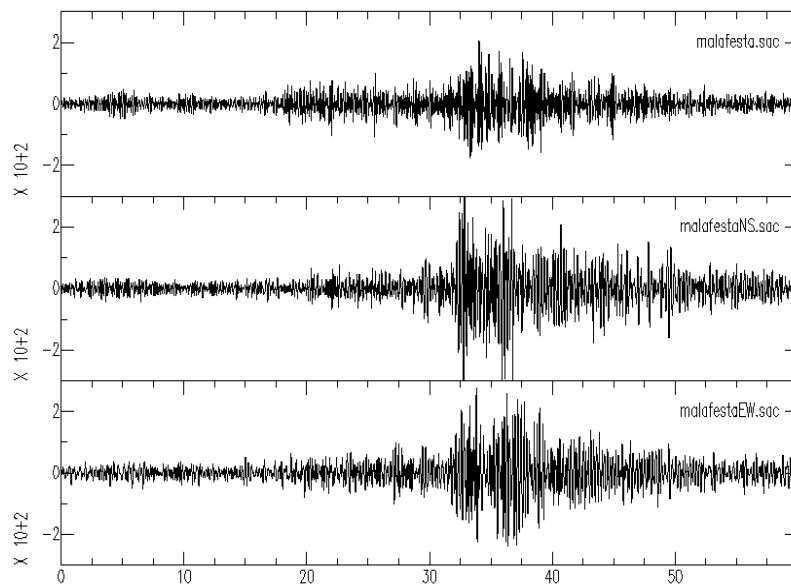
Malafesta (top) and Bibione (bottom) stations
vertical, radial and transversal components
same amplitude axes, time in seconds



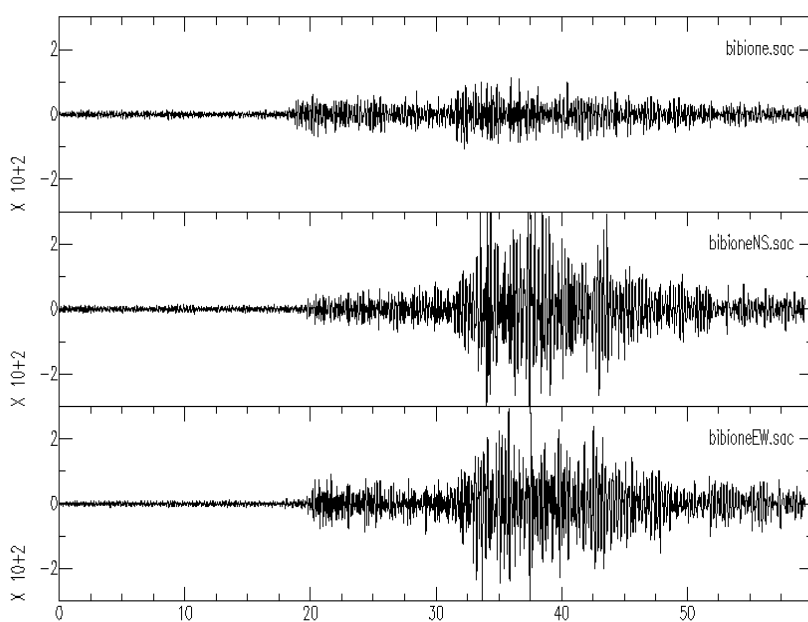
Galliera Earthquake

Malafesta (top) and Bibione (bottom) stations
vertical, radial and transversal components
same amplitude axes, time in seconds

SAC 1

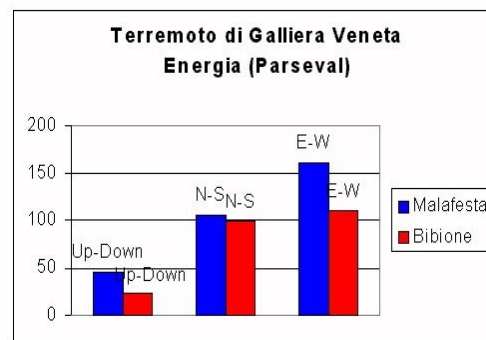
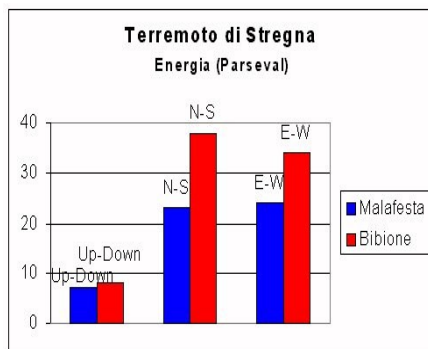


SAC 1



▣

For lateral earthquakes there are no significant differences between the two stations, in term of amount of energy (graphs below). This suggest, as attended, the different seismic behaviour for the studied area are evident only for events coming from the N-NE seismogenic zones.



In the frequency domain, the vertical component of the Earthquakes records do not significantly defer. In the case of the N-NE earthquakes (e.g. Gemona Earthquake, Fig.12a/b) there are a slow decay in higher frequency (>10Hz), linked to inter- stations distance.

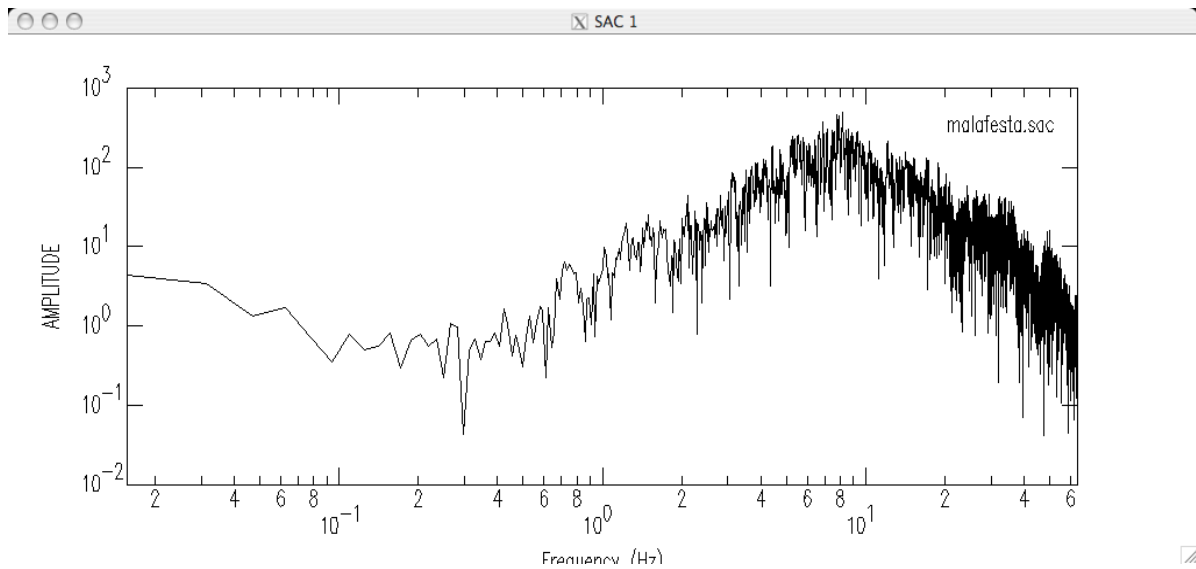


Fig.12a: FFT of Gemona Earthquake at Malafesta station

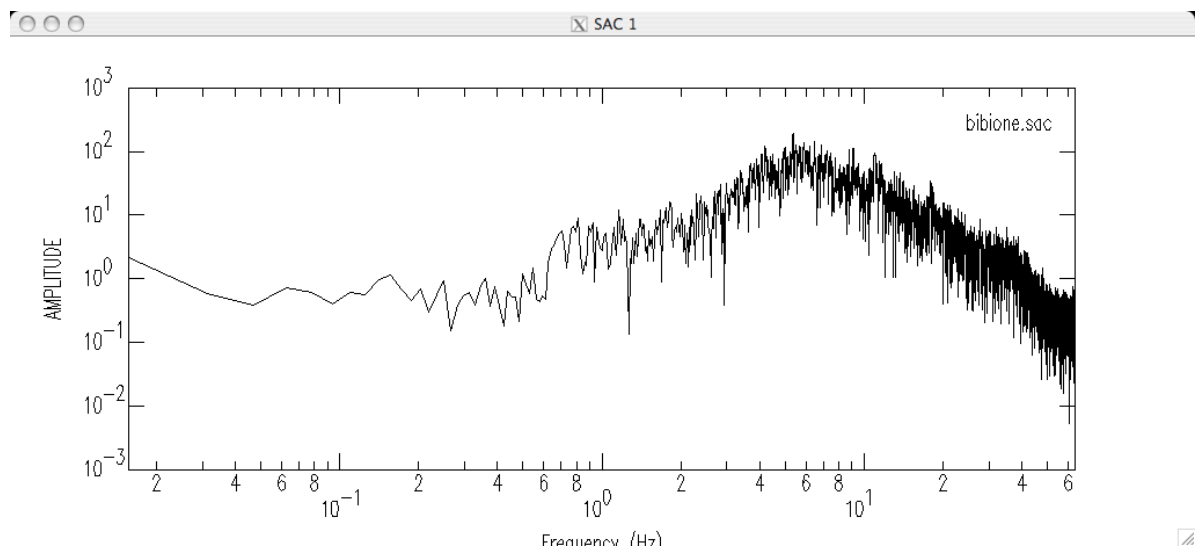


Fig.12b: FFT of Gemona Earthquake at Bibione station

For the 'lateral' Earthquakes (e.g. Stregna Earthquake fig 13a/b) the epicentral distances between the receivers are more or less the same. As attended no difference in frequency domain is evident.

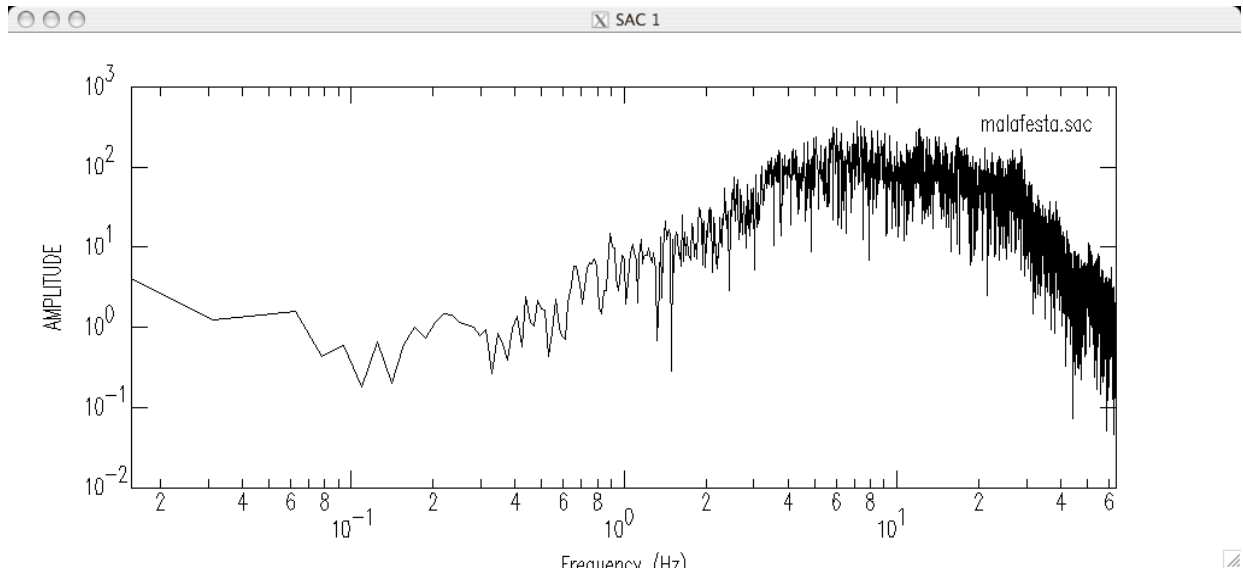


Fig.13a: FFT of Stregna Earthquake at Malafesta station

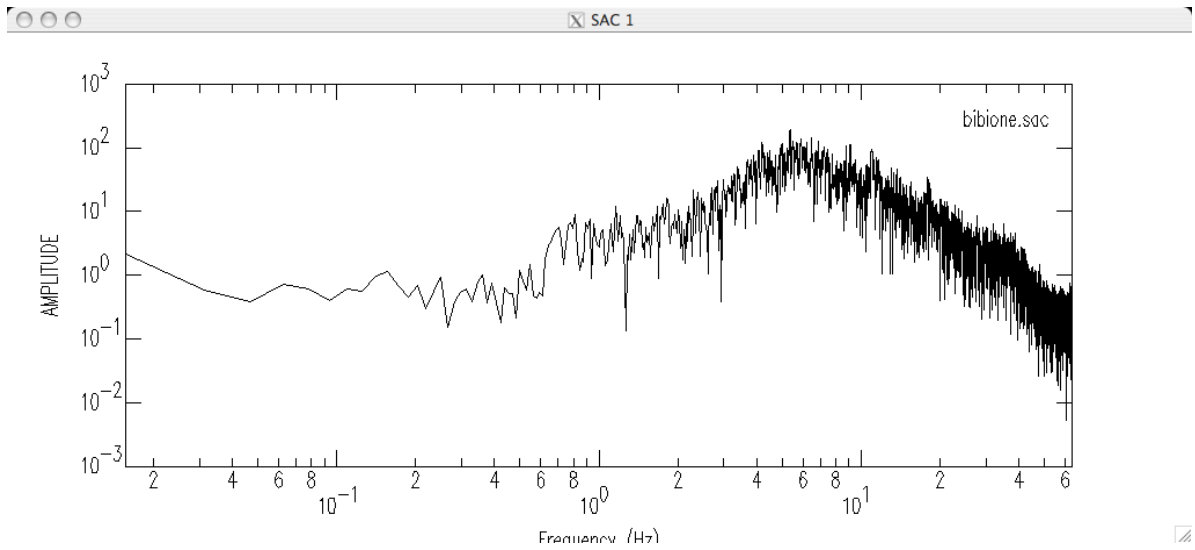


Fig.13b: FFT of Stregna Earthquake at Bibione station

Chap.3

Experimental Activities

The H/V ratio for the analysis of seismic noise

In the studied area the worldwide known H/V technique has been applied for 2 main purposes: the first was, basing on the simple geological conditions, the possibility of detect strong impedance contrasts, the second to estimate the natural frequency of subsoil. Thanks to tithes of measurements we tried to consider limits on the application of this technique, in a environment of lowland plain. Our conclusion is that we can consider the so called 'Nakamura' method, in condition of very deep alluvial basin that involve sediments (from clay to gravel), a good and speed heterogeneity estimator, but with several limitations.

3.1 Microtremors

The surface of the Earth is always in motion at several seismic frequencies, even without Earthquakes. These constant vibrations of the Earth's surface are called microseisms or microtremors.

The amplitude of these microtremors is, with some extreme exceptions, generally very small. Displacements are in the order of 10^{-4} to 10^{-2} mm ; far below human sensing. Although they are very weak, they represent a source of noise to researchers of earthquakes seismology; if amplifier gain is increased to record earthquake signals from far source, the amplitude of microtremors proportionally increases, and the desired earthquake signal is buried in the noise. Elimination of this background noise is technically extremely difficult or impossible to achieve. Therefore earthquakes researchers call microtremors 'seismic noise' or simply 'noise'.

It was until the late nineteenth century that seismologists could use real seismometers to observe earth's motion. Since then microtremors have been a focus of their strong interest, as in evidence by the large numbers of published works. Much of the research concerns the source of the vibration and variation of the character of the vibration depending on time and location (as this work does in a such way). From these researches we know that microtremors are caused by daily

human activities such as movement of machinery in factories, motor cars, people walking and by natural phenomena such flow water in rivers and sea waves (especially in this work), wind, variation of atmospheric pressure etc. Thus microtremors are not a natural phenomenon *senso-stricto*, as human activities constitute some of their sources. However, microtremors are now not regarded as nuisance noise, but rather a useful signal.

Both human activity and natural phenomena (such as climate and oceanic conditions) vary with time. Accordingly, microtremor activity varies over time. This variation is very complex and irregular and not repeatable.

When microtremors are observed simultaneously at several spatially separated stations, it is noted that these tremors are not completely random and that some coherent waves are contained in the records. In other words, microtremors are an assemblage of waves travelling in various directions. In fact, Toksoz and Lacoss (1968) clearly demonstrated from the data of large-aperture seismic array (LASA) that microtremors are an assemblage of body waves and surface waves.

3.1.1 Power Spectra of Microtremors

The microtremors originating from human activities are dominated by the components with periods shorter than 1 second and evident diurnal variation in amplitude and period appeared.

On the other hand, the microtremors due the natural phenomena, such as climatic and oceanic condition, have dominant periods greater than one second corresponding to the vagaries of the respective natural phenomenon.

A detailed analysis reveals that microtremors vary depending upon location. The microtremors survey method has been devised to focus on this variation. In the 1960s explanation of power spectra were proposed to the effect that the high power level of the low-frequency components (below 1 Hz), while the higher frequency components (above 1Hz) were attributed to human activity and climatic conditions. We believe that in our specific case, considering the low depth of Adriatic Sea, the sea wave dominates our noise field till 2- 3 Hz.

3.1.2 Temporal and Spatial variation of Microtremors

Microtremors are variable phenomena in space and time. They show complex variations, but the degree of complexity does not vary during the recording period of few minutes. For the low frequencies the differences between daytime and night is minimal. On the other hand the difference is relevant for higher frequencies, and it is more clear in urban environment, where the human activities are predominant.

The temporal variation of microtremors of low frequencies is in good relationship with atmospheric pressure and sea level.

The higher frequencies microtremors are linked to human activities, and suffer a strong diurnal variation. As can be obviously be understood, higher frequencies microtremors suffer also spatial variation.

3.2 H/V Basic

The technique of horizontal to vertical spectral ratios of microtremors, was first applied by Nogoshi and Igarashi (1970,71) and popularized by Nakamura (1989). The method was firstly used to estimate site effects, based on the presumed stationary of the vertical ground motion component. We do not believe in this kind of application (as explained after), but the technique proved to be effective in estimating fundamental periods of sediments (Field and Jacob 1993). However, in the author's opinion, this technique lacks a rigorous theoretical background still now.

Microtremors observed at the ground surface consist of body and surface waves, with their proportion really not clarified. Is a fact, proved even in this study, that the H/V ratios peaks converge to fundamental mode Rayleigh waves, estimated from geological data. In addition Lachet and Bard (1994) indicated with numerical simulation that the H/V ratios at the longer periods were governed by fundamental Rayleigh waves. The Konno and Omachi (1998) study indicates very well the relationship of Rayleigh wave and the H/V ratio as function of the impedance contrast.

If we consider microtremors site effect linked to S wave vertically incident (SH 'Nakamura hypothesis'), we can explain the site effect given in terms of a simple Transfer Function :

$$F_i(\omega) = 1 / \cos(\omega H / V_s)$$

with H depth of refractor and V_s shear wave.

A simple two-layers model explains its basic principle: a hardrock basement covered by a soft sedimentary layer of thickness m and shear velocity V_s . Resonant frequencies of this system occur for thickness that are uneven multiples of $\lambda/4$.

So the transfer function has maxima at frequencies fr:

$$f_r = \frac{n V_s}{4m} \quad (n = 1, 3, 5, \dots)$$

In fact, in a sedimentary layer, the relation between fundamental period and transfer function may be written:

$$F_i(\omega) = 1 / \cos(\omega H / V_s) \quad \text{Transfer Function} \quad (1)$$

$$\omega H / V_s \rightarrow \pi/2 + n \pi \quad \text{Resonance condition} \quad (2)$$

$$\omega_0 = \pi V_s / 2H \quad \text{Fundamental Frequency} \quad (3)$$

$$T_s = 2 \pi / \omega_0 \quad \text{Fundamental Period} \quad (4)$$

Some authors (Ibs-Von Seth and Wohlwnberg 1999) suggest to define the peak resonant frequency in function of Vs with :

$$V_s = V_0 (1+Z)^a$$

with 'a' empirical parameters. It is used for infer the thickness of sediment when only the upper shear wave velocities are known. We preferred to consider this methodology as his qualitative nature suggest, considering the Vs value as a medium of all the sediments layer. In case of complex geology (e.g more seismic refractors or non plane geometry) the application of this technique meet several limitations (Della Mora 2007).

Is authors opinion, after the experimental work of this Thesis, that H/V technique lacks of rigorous theoretical explanation, and so it is not always applicable, but still have many advantages. The speed and proved possibility of detect fundamental soil period is a great information, not easily detectable in other way, but relate it to subsoil geometry is not linear. However we found many experimental good relationship between the H/V ratio and the known geology. We believe that, in case of wide unknown areas, it is a unique and speed method to estimate the subsoil heterogeneity, more than the real geometry. Leak impedance contrast, complex geology in terms of many refractors or non plane geometry, and artificial noise source, seems to be the strongest applications limits for this methodology.

3.3 Synthetic Test on H/V

To verify the Rayleigh influence on the H/V ratio we performed a synthetic test for the known geological condition of our test site.

We assumed a model similar to the studied area, with 500 m of sediment ($V_s=600\text{m/s}$) upon a bedrock ($V_s=2000\text{m/s}$). Then, we use the modal summation technique (Panza 1985) applying a point source. Eigenfunctions and structural model is shown in Figure 14.

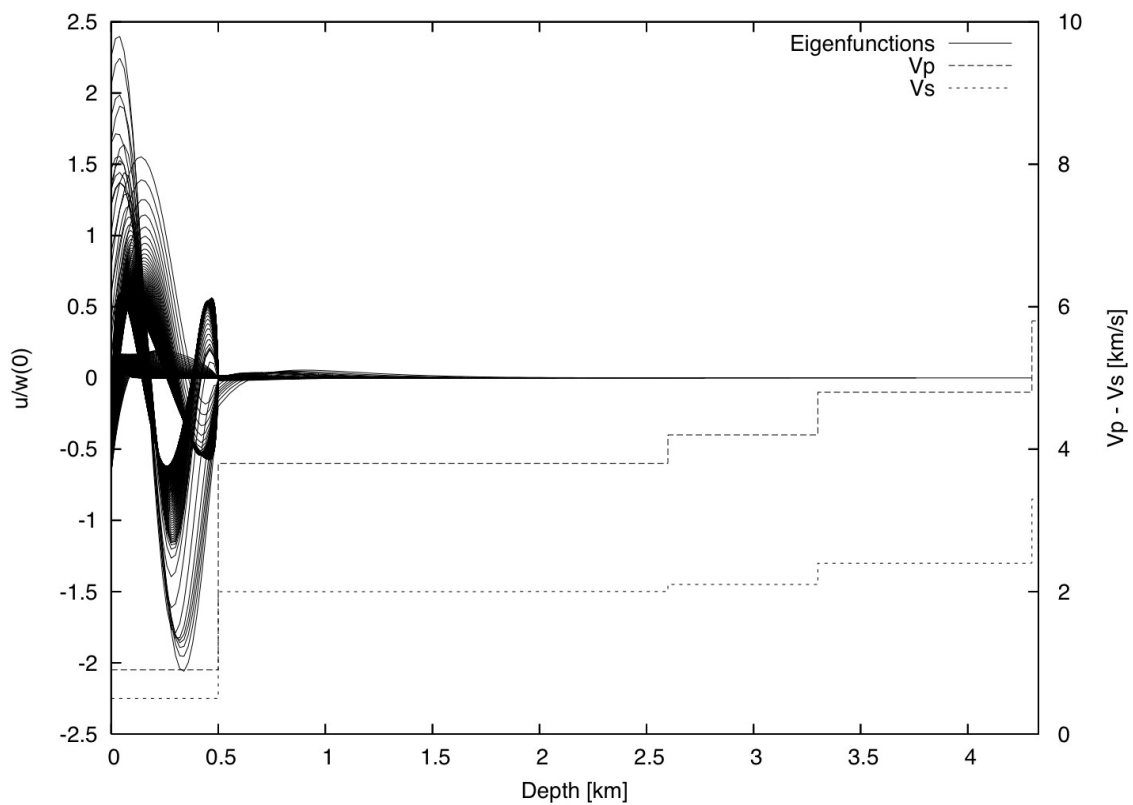


Fig.14 Computed Eigenfunctions for a given structural model, point source.

Lachet and Bard (1994) and Konno and Omachi (1998) first suggest H/V ratio is governed mainly by fundamental mode Rayleigh wave. In fact, especially in longer period in presence of high velocity contrast (condition experimentally necessary) it is demonstrated H/V ratio show a maximum peak when Rayleigh ellipticity invert his motion (prograde to retrograde). The experimental H/V noise analysis performed in the site area gave us a fundamental frequency of ca 0.5 Hz. The synthetic computation of H/V ratio, even for a single point source and not for noise, confirm this value (Fig.15).

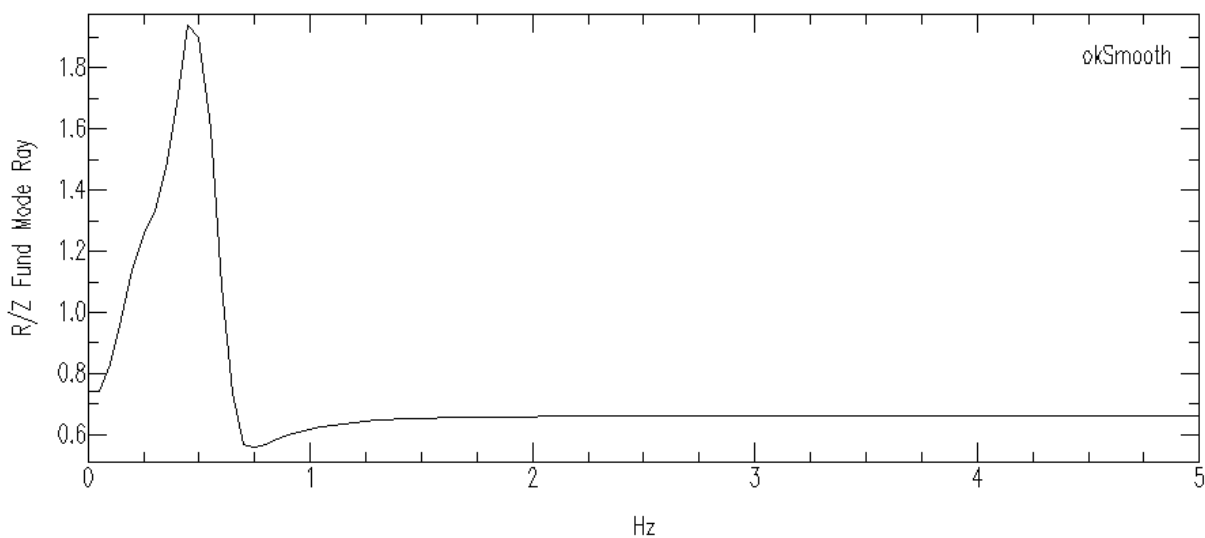


Fig.15 Synthetic R/Z ratio of Fundamental Rayleigh Mode for the structural model of fig.14.

If we analyze Rayleigh fundamental mode ellipticity for the given structure, the same fundamental frequency (0.5Hz) appear (when ellipticity reach his maximum, and change his polarity). This implies, according Konno and Omachi 1998 conclusions, the strong relationship between H/V ratio and Rayleigh wave ellipticity.

Our test confirms, in conclusion, that the contribute of body and surface wave in a seismic noise analysis are not quantifiable.

The formula (1)-(4), that implies SH wave vertically incident at the surface, is not always applicable and, above all, we can not know when.

The evidence is that Rayleigh wave strongly influence noise acquisition, but the easy frequency/Refractor depth relationship (4) is experimental confirmed in many case. Our conclusions is H/V ratio technique still remain a phenomenon without strong theoretically backgrounds, and this implies the methodology lacks of quantitative application.

The experimental results obtained proved that, instead, qualitative speed application for homogeneity estimation is a valid use of noise Horizontal to Vertical Spectral Ratio.

3.4 H/V in the studied area

We designed an H/V acquisition program for all the studied area (Fig.16). The purposes were to define the sediments thickness and estimate the fundamental period of subsoil. First of all we found a calibration of the method where the bedrock depth was known from drill-point. Than we try to estimate the Miocene Bedrock/Quaternary limit in the studied area. In effect, we demonstrated that the H/V ratio peaks shift to higher frequency in the north zone, were less sediments thickness is attended, and show more than one peak were strong impedance contrast are present inside the each sediments (e.g. sand- gravel).

In a multi layers system the H/V contributes are not linear, and the equation (1) decades. In this work we didn't invert the noise measurements for stratigraphy purposes, but we use them only to observe local inhomogeneities responses.

In conclusion the method find a good application in this lowland environment but is still constrain as a qualitative estimation.

We consider, instead, the fundamental sub soil period knowledge is an important improvement in the seismic zonation of an area.

We used 2 TROMINO tromographs (see chap.2). We focused our research mainly on 4 sites :

- Villanova della Cartera

01257.2232 Long E

4550.1577 Lat N

- S.Michele al Tagliamento

. 01259.4007 Long E

4545.8023 Lat N

- Marinella- Ca Bianca

01301.4893 °Long E

4541.0059 °Lat N

- Bibione

01303.8676 °Long E

4538.0371 °Lat N

In every site we performed many noise acquisitions, in different date and time, in order to verify the stability of the H/V ratio. In the S.Michele site we measured even during night, to verify the stability of a strong secondary peak that could be artificial.

Every measurement was of 30 minutes of acquisition, with 128Hz sampling. We follow however the SESAME indication in terms of distance from building and soil- instrument coupling.

DATA ANALYSIS

-time windows analysis 20s

-smoothing with triangular window (5% ampl. of central frequency)

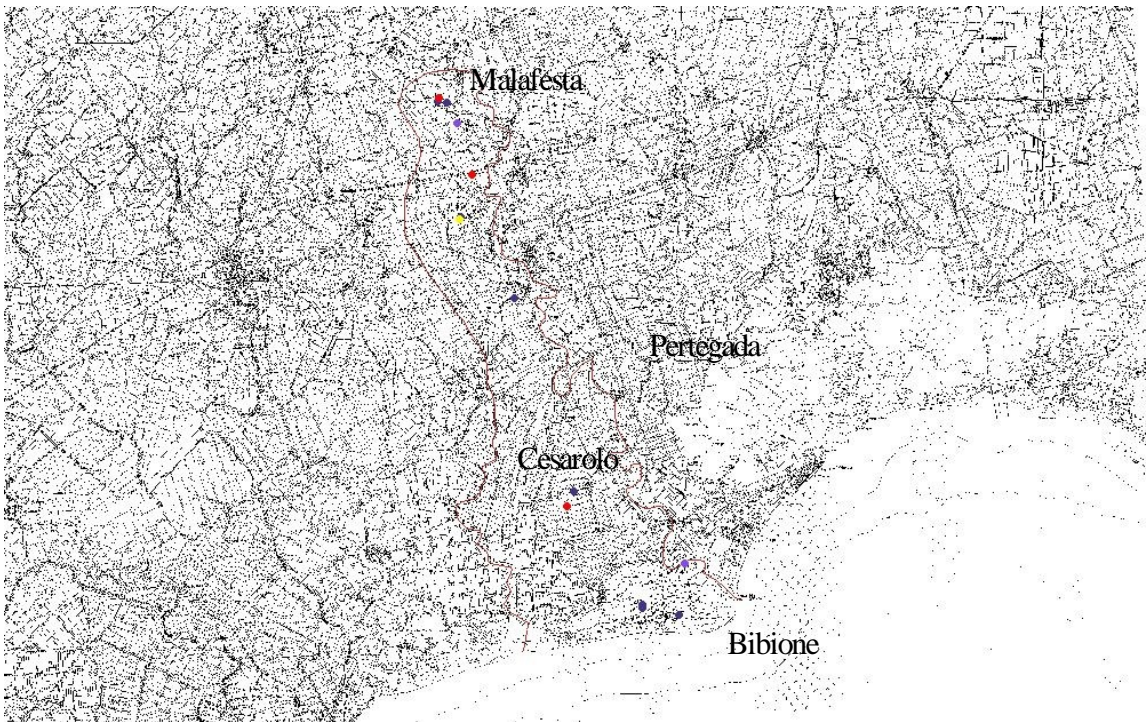


Fig .16 H/V point analysis in the studied area and main localities.

3.4.1 Results

As explained before, we used the direct knowledge of the subsoil, by well-point stratigraphy, to calibrate the ambient noise measurements. The Agip deep well of Cesarolo gave us the unique precise known thickness of all the sedimentary body (478 m). A thermal water- exploitation project performed interesting drills, less deep than the Cesarolo well, but useful to define other strong impedance contrast inside the sediments (e.g. gravel levels).

The H/V ratios for the Agip 'Cesarolo' well point show clearly a peak at 0.44 Hz. Considering the expression (4) the sedimentary basin in this point should be characterized by a medium shear waves velocity of 800 m/s. It seems to be a reasonable value considering the lithology of the sediments, the fining upward deposition, and the deep constipation of the sand/gravel deposits. Previous reflection seismic study (Della Vedova et al. 2001) close to the area (Pertegada), found a very strong impedance contrast not at the base of quaternary formations, but deeper, at the Langhian roof. This sedimentary discordance define the contact of the Cavanella formation (Limestone). It could be possible that the main refractor, that is linked to H/V peak, is so deeper than 480 m, and probably

between 500 and 600m. In this case the medium Vs of our upper formation could be higher (1000m/s). It is a necessary consideration, without defined impedance knowledge, that remark the qualitative but speed characteristic of this methodology. Other applied methodologies results seem to be consistent with very high shear velocity of sediments.

As explained, considering the medium velocity of the sediments estimated, we can perform a qualitative idea of the bedrock deepness in the other points of measurements.

The H/V peaks related to this deep contrast shift till 0.38 Hz were a deeper bedrock is attended (ca 570 m) and reach the 0.44 Hz of the Cesarolo structural high, that lifts the Miocene roof up to 478m (Fig.17).

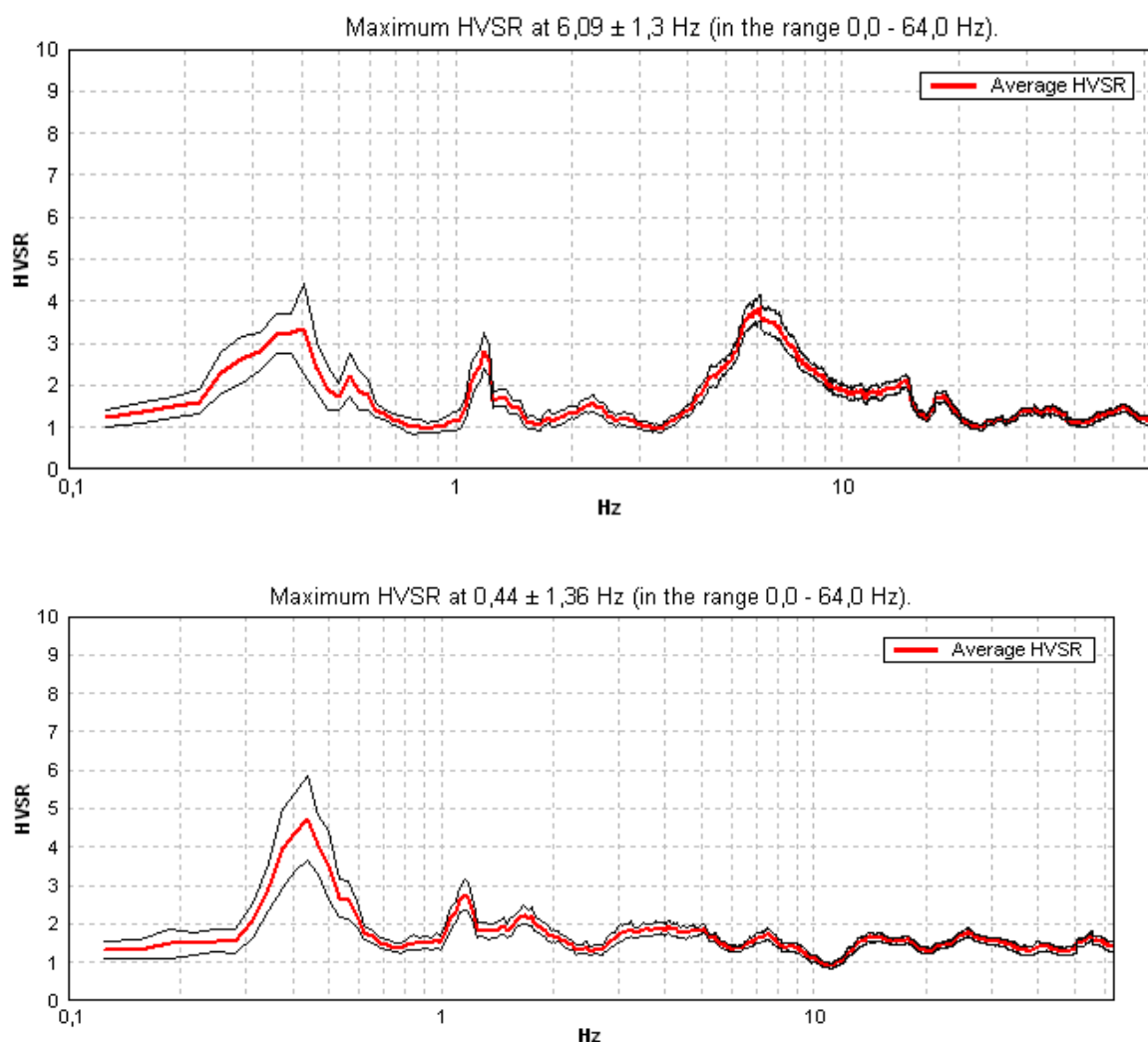


Fig.17 H/V ratio of Villanova (top, peak at 0.38Hz), and Cesarolo (bottom, peak at 0.44Hz)

In strictly seismological terms, this weak difference of bedrock roof, considering the extension of more than 300 qkm of the studied area and the deep structure involved, is irrelevant. But we consider that to estimate rapidly and in a passive way the bedrock geometry, though in a qualitative way, is instead a relevant information.

The experimental field aims involved even the resonant period of the subsoil definition, in order to consider it in relationship with the building of the area.

Fig.18 shows S. Michele al Tagliamento and Bibione H/V ratio, obtained with the same analysis of fig.17.

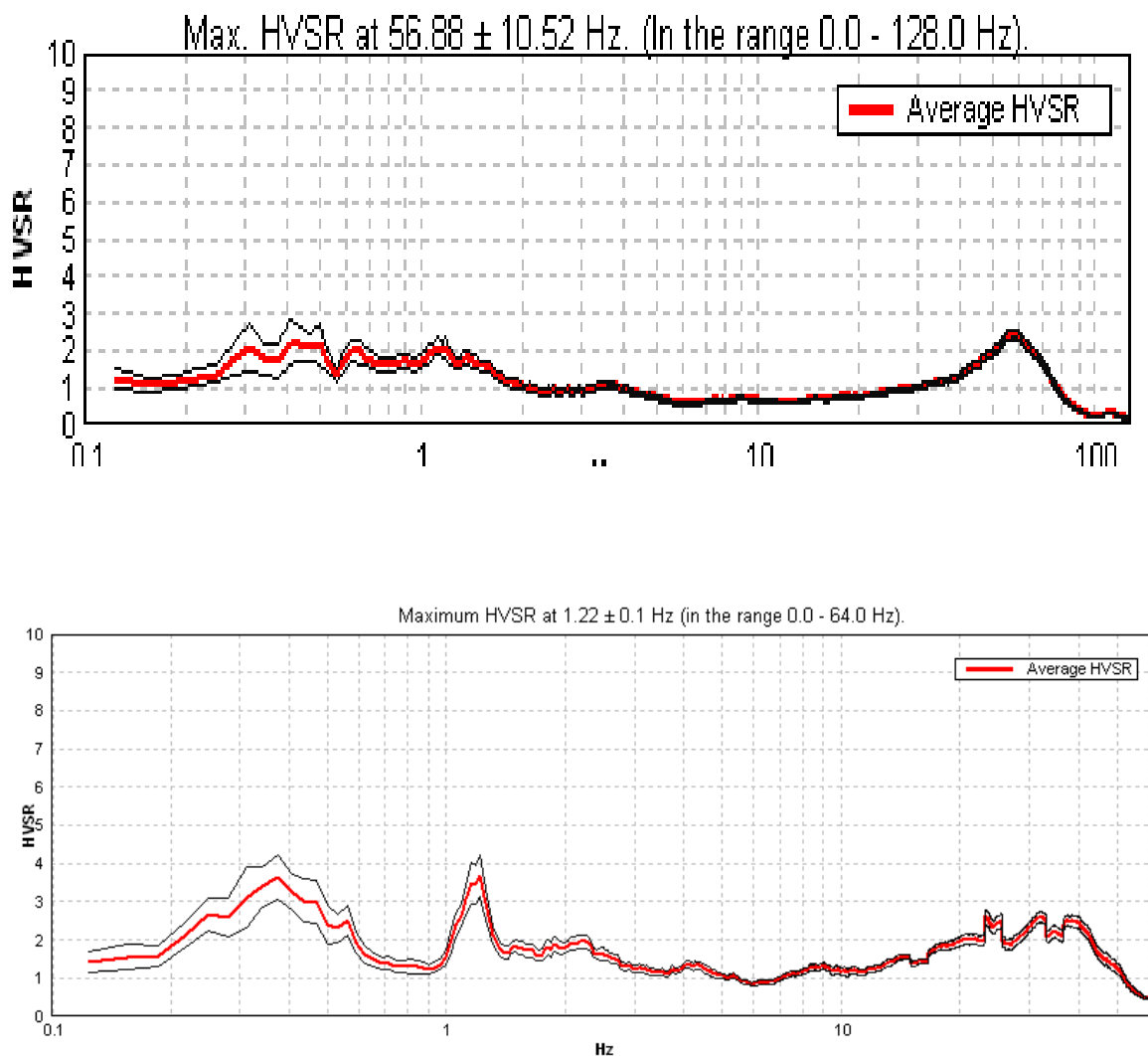


Fig. 18 H/V ratio at Bibione (top) and S. Michele al Tagliamento (bottom)

As figures show, sites like Villanova and S.Michele are characterized by strong secondary peaks near 1.5 Hz. This peak does not appear in Cesarolo or Bibione measurements. Even if not referred to the bedrock, this secondary stable peak could be important in terms of building seismic shocked behaviour. This secondary peak could be referred to a secondary impedance contrast into the sedimentary basin. A sufficient contrast in our deposition environment could be referred to the gravel levels in contact to clay and fine sand. Several drilling in the studied area and in the Latisana area (from the north S.Michele territory to Pertegada) found a gravel level between 120 and 160m that we consider in good correlation with the frequency of the H/V peaks. Fig.19 shows several well-point. Wells 4, 6 and B are referred to S.Michele al Tagliamento area. Around 150- 180 m depth a gravel level appear continuous. Probably the secondary peak evident in H/V ratio is related to this level. No quantitative relationship or stratigraphy conclusion could be inferred by this noise acquisition but a inhomogeneities subsoil conditions is visible.

Previous seismic study (Della Vedova et al. 2001) found this gravel reflector (Fig. 20, in yellow). Trusting in this relationship the method seems to be very sensible even for complex stratigraphy, but we have rare direct informations of the subsoil, and we consider the experimental data not sufficient to confirm these hypothesis.

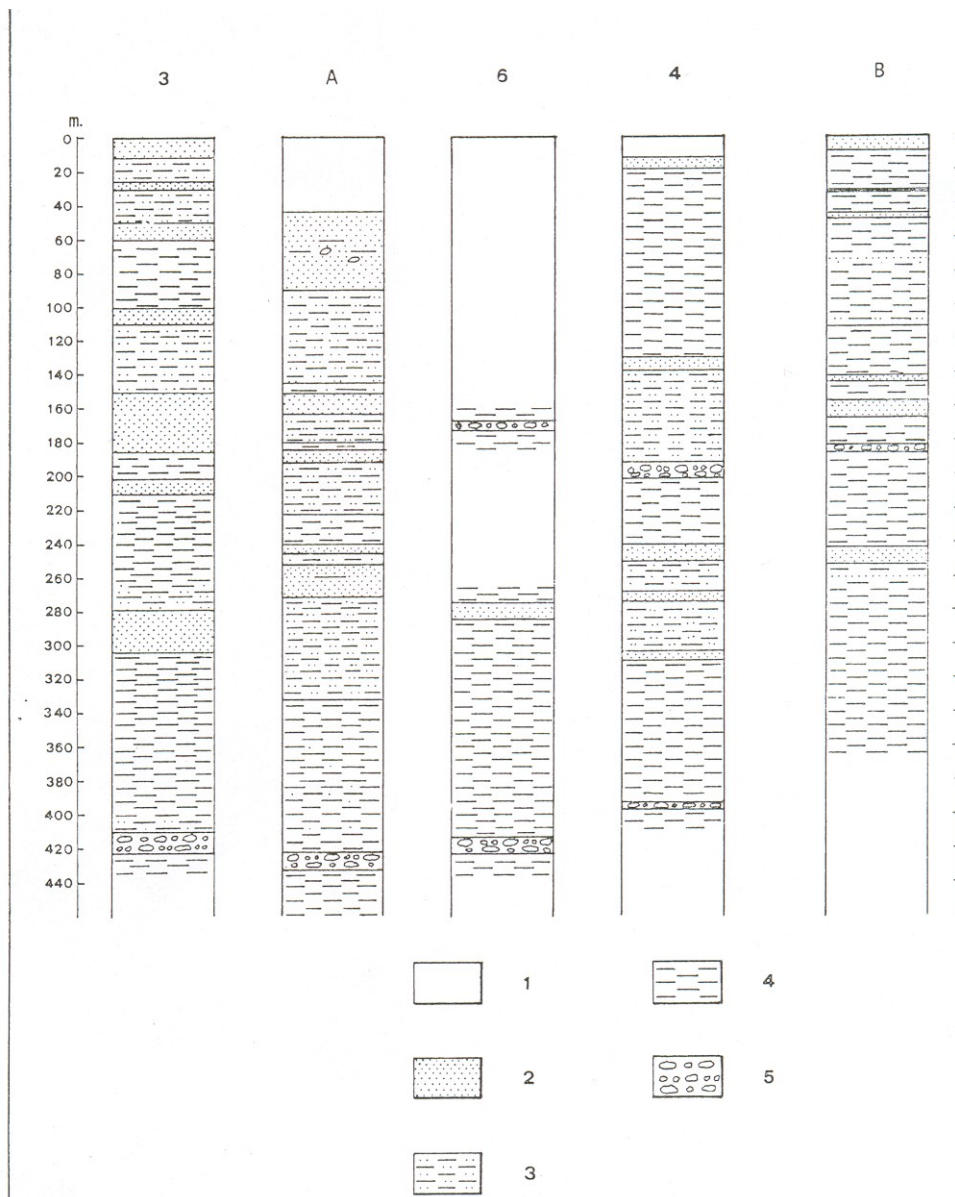


Fig.17 Lithological logs of wells in the studied area. 1: No data, 2: Sand, 3: Clay and Sand, 4: Clay, 5: Gravel

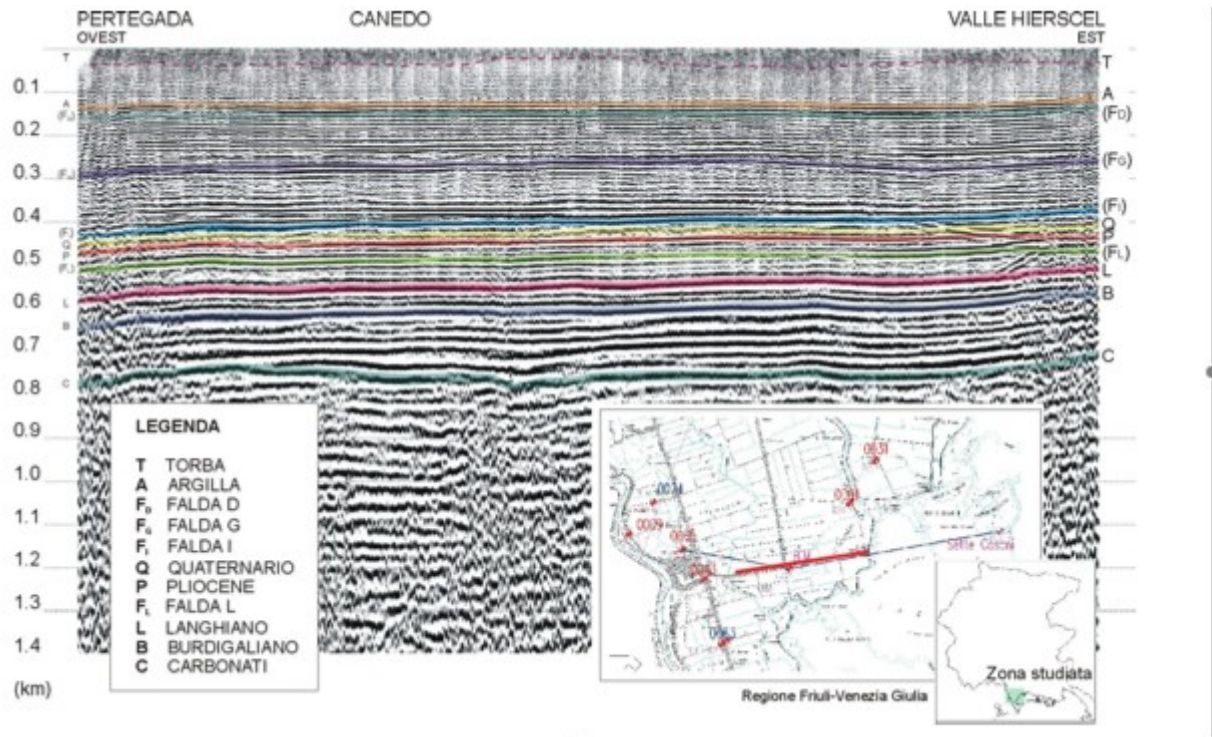


Fig.20 Seismic reflection section near the studied area: in evidence seismic reflectors (Della Vedova et al 2001).

3.5 H/V Technique on Buildings

In recent time the H/V technique is used even to define the fundamental period of existing building (Mucciarelli et al 2001). The method is able to evaluate building resonant period, considering ever the vertical component of motion stable and applying it to the top of the building.

This method has been applied on 3 different types of building in S. Michele al Tagliamento. We used 2 Tromino tromographs, one on the base of the building and one at the top, in simultaneous acquisition of ambient noise for 30 minutes.

We used 2 instrument to verify the influence of the soil resonant period on the top building measurement. We verify, as showed below, that in the case of the H/V ratio on soil present relevant peaks, the H/V ratio measured on the top of a

building is strongly influenced by the soil one.

The use of 2 instruments in simultaneous acquisition permits to perform the ratio between the horizontal components of the top and the base of building. This measurement permits to eliminate the contributes of soil vibration from the building specific ones. The building real fundamental period is, in this way, rapidly defined.

Let's consider a test in a 4 floor building. Fig 21 and Fig 22 show the H/V ratio on at base and top of a building in S.Michele al Tagliamento.

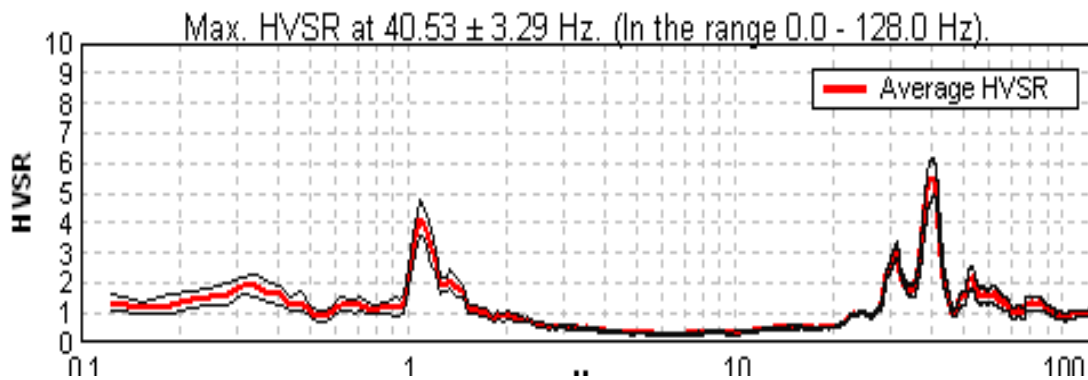


Fig 21 H/V ratio at base of building

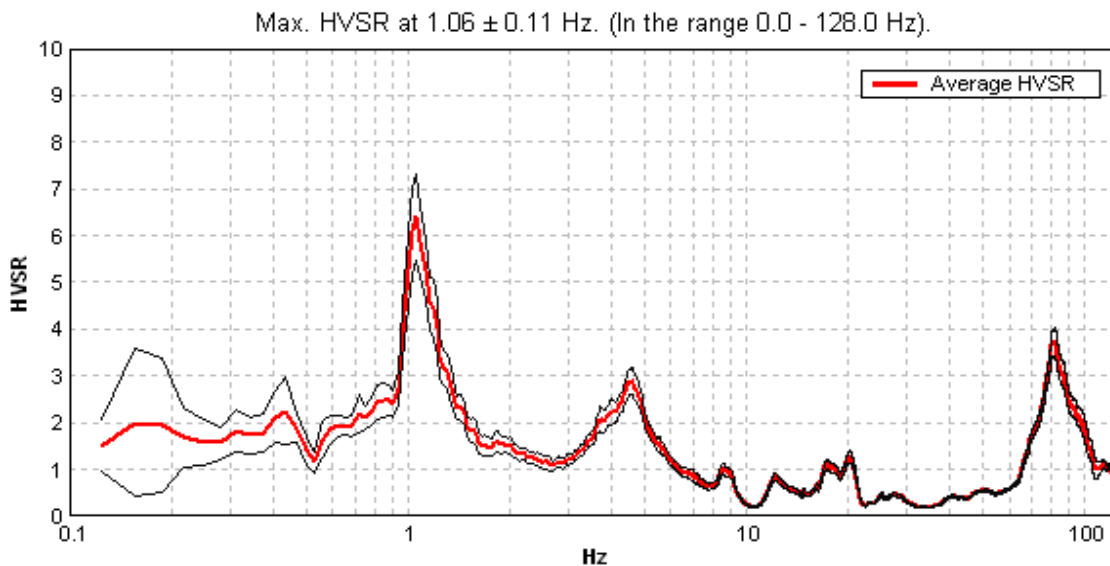


Fig.22 H/V ratio at top of building

It is evident that the predominant 1 Hz peak measured at the top of the building is not refer to the building structure but to soil fundamental period, evident on the H/V at base.

If we performed the ratio between the two stations, taking horizontal components medium and considering vertical component stable, we can 'isolate' the system building from soil resonance.

Fig.23 shows the result of ratio between Horizontal components at Top and at base. 4.8 Hz first peak is in good agreement with 4 floor fundamental attended frequency.

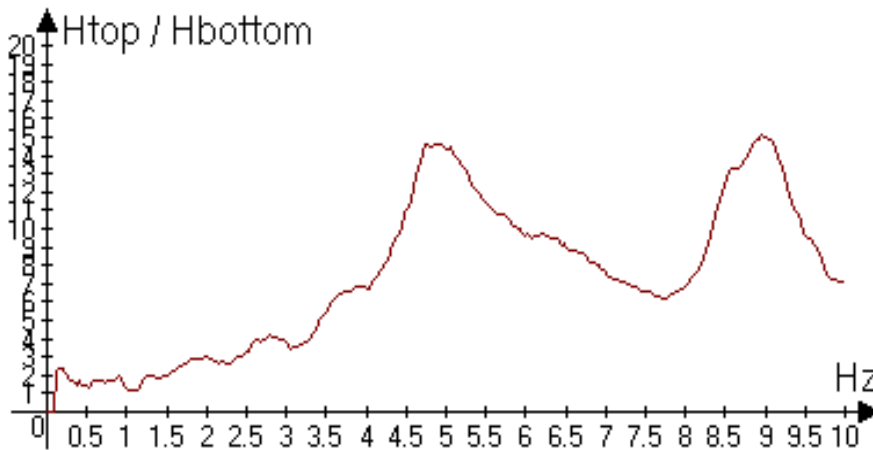


Fig.23 Ratio between horizontals components at top and base of a 4 floor building.

Chap. 4
Experimental Activities
Controlled source FTAN

4.1 Brief introduction to surface waves

The so called surface waves are of two types. They are generated by body waves incident surface of the Earth, and they are named Rayleigh waves and Love waves. Rayleigh (1885) predicted the existence of surface waves when he mathematically modelled the motion of plane waves in an elastic half-space. Love (1911) investigated the effect of a surface layer and discovered the other important surface wave, which was named after him.

If a disturbance, such as an earthquake or explosion, occurs, a significant amount of the seismic energy is trapped near the surface and is transmitted as surface waves which travel as guided waves. They may be regarded as the result of the addition and interference of waves incident and reflected at the surface, and their amplitude decrease with depth. Rayleigh wave ground motion is elliptical, as for a water wave; Love waves are faster and are shear waves like S body waves, but vibrate only in the horizontal plane (horizontally polarized SH). Cause surface waves travel in two dimensions, and not three as for body waves, their amplitude decrease more slowly with distance and they tend to dominate recordings also in short distance. Since the first seismogram computed by Lamb (1904), it is well known that the largest surface ground motion for an impulsive vertical point force applied to the surface of a half-space is an undispersed Rayleigh pulse travelling with a velocity of 0.9, 0.95 V_s (for typical Poissons ratio of 0.2-0.4). Surface wave motion, in fact, are the largest of any arrivals on seismograms. The amplitude reduction with distance of surface waves are $r^{-0.5}$ (with r distance), instead the three dimensional spreading of body waves, which amplitude decrease as r^{-1} (with r distance). These reasons intuitively suggest that the most suitable methods for shallow V_s measurements are based on Rayleigh waves measurements.

Surface waves are easily recognized on seismograms as they have the largest amplitudes, but they are difficult to analyse because their main characteristic, dispersion, is a function not a single value parameter. Surface wave analysis needs identification and separation of signal from noise and measurement of phase and group velocities which depend on frequency.

The phase velocity $c(\omega)$ and group velocity $U(\omega)$ are defined as:

$$c(\omega) = \frac{\omega}{k(\omega)} \quad U(\omega) = \frac{1}{\frac{dk(\omega)}{d\omega}} \quad (5)$$

being $k(\omega)$ wave number. The functions $c(\omega)$ and $U(\omega)$ are named phase and group velocity dispersion curves, respectively, and are related by:

$$\frac{1}{U(\omega)} = \frac{1}{c(\omega)} + \omega \frac{d}{d\omega} \left(\frac{1}{c(\omega)} \right) \quad (6)$$

On a seismogram recorded at a receiver distant x from the source, phase and group velocities can be computed as:

$$U(\omega) = \frac{x}{\left[t_0 + \frac{d\phi_R(\omega)}{d\omega} - \left(\frac{d\phi_S(\omega)}{d\omega} \right) \right]} \quad (7)$$

$$c(\omega) = \frac{x}{\left[t_0 + \frac{\phi_R(\omega) - \phi_S(\omega) \pm 2\pi N}{\omega} \right]} \quad (8)$$

being t_0 the delay of the analysed signal relative to the origin time, ϕ_R e ϕ_S signal phase at the receiver and source, respectively, at radial frequency ω , and N an integer number to be empirically determined. Generally speaking $\phi_S(\omega)$ is lightly depending on ω , hence $d\phi_S(\omega)/d\omega$ can be neglected for practical uses, while, mostly at high frequencies, the evaluation of N can be problematic.

4.2 Basic of FTAN method

Prof. T. Nunziata, University of Naples, published an exhaustive paper on Technical and Environmental Geology (2005), where FTAN method are master explained. The most important part are below reported.

FTAN (Frequency Time Analysis) method represents a significant improvement, due to Levshin et al. (1972; 1992), of the multiple filter analysis originally developed by Dziewonski et al. (1969) and can be applied to a single channel to measure group velocity, (and, if the source is known, phase velocity) even when there is higher modes contamination. FTAN is appropriate to process surface wave data both for the identification and the separation of signals, and for the measurement of signal characteristics other than phase and group velocities, like attenuation, polarization, amplitude and phase spectra.

FTAN method is successfully employed both in seismological and engineering field (e.g. Nunziata et al., 1999a,b,c), and it is useful even in defining V_s profiles of shallow geological structures. Analysis consists in extracting group velocity fundamental mode of Rayleigh waves artificially generated by an impulsive source, by 1 vertical geophones with resonant frequency of 1 Hz or lower.

V_s profiles could be inferred by a direct model (trial and error method) but detailed profiles with depth are obtained only from the non linear inversion (hedgehog method) of the average dispersion curve of Rayleigh group velocities.

4.2.1 Signal analysis

FTAN analysis is performed on a signal $W(t)$, instrument response corrected (Fig. 24). The first step consists in identifying on the seismogram the Rayleigh dispersive wave and computing Fourier transform, $K(\omega)$:

$$W(t) = |W(t)|e^{i\phi(t)} \leftrightarrow K(\omega) = |K(\omega)|e^{i\psi(\omega)}$$

where $|W(t)|$ and $\phi(t)$ are instantaneous amplitude and phase. For narrow band signals, where the band width is much lower than the dominant frequency, $|W(t)|$ and $\phi(t)$ represent the envelope amplitude and carrier phase, respectively.

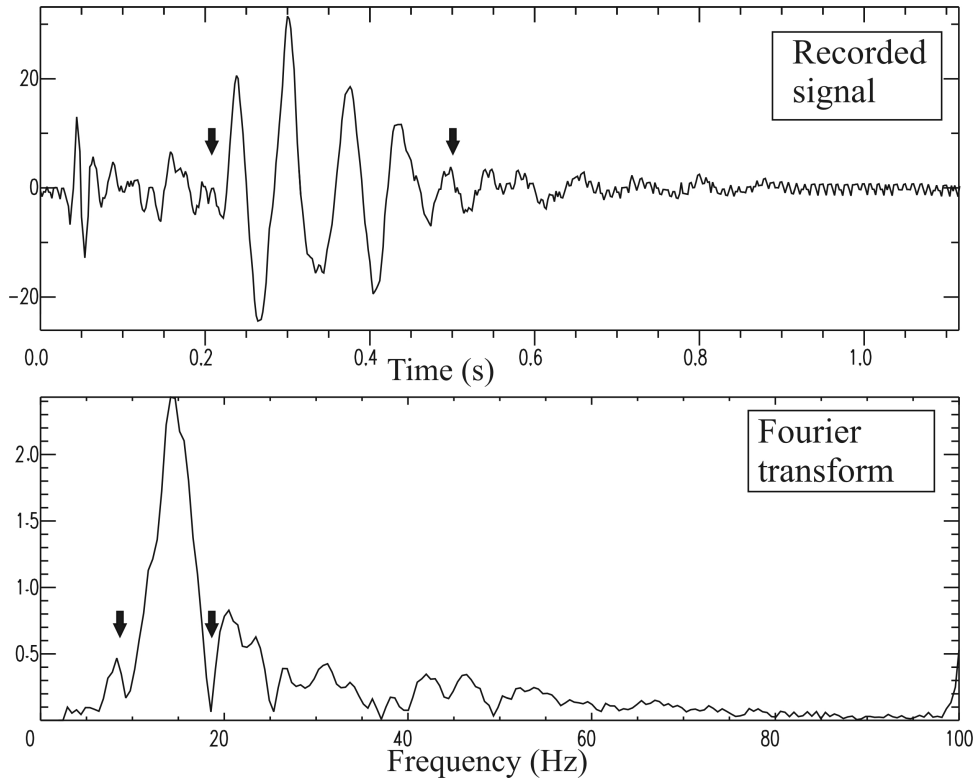


Fig. 24 – Fourier amplitude spectrum of a signal recorded with 80m offset, instrument response corrected (1Hz vertical geophone, 70% damping). Rayleigh signal and spectral band are between the arrows (Nunziata C. 2005).

A main characteristic of surface wave signal is the group time $\tau(\omega) = -\frac{d\psi(\omega)}{d\omega}$,

because strictly related to the medium properties. The phase spectrum of surface waves in a laterally homogeneous medium is:

$$\psi(\omega) = -k(\omega)r + \psi_s(\omega)$$

with $k(\omega)$ the wave number, r the distance travelled by the wave and $\psi_s(\omega)$ the source phase.

Then the group time is:

$$\tau(\omega) = -\frac{d\psi(\omega)}{d\omega} = \frac{r}{U(\omega)} - \frac{d\psi_s(\omega)}{d\omega} \quad (9)$$

This equation explains why the name group time, as related to group velocity.

The function $\tau(\omega)$ is named spectral dispersion curve of the signal. In addition, as the source duration is short relatively to $\tau(\omega)$, a constant source phase (equal to zero) can be assumed and simplify the group time equation to:

$$\tau(\omega) = \frac{r}{U(\omega)} \quad (10)$$

Hence the study of velocity characteristics in a medium needs the measurement of $\tau(\omega)$ and $\psi(\omega)$ of the signal.

In the second step, the dispersed signal is passed through a system of parallel relatively narrow-band filters $H(\omega - \omega^H)$ with varying central frequency ω^H . Each resulting signal will concentrate around the time $t = \tau(\omega^H)$, for any signal with a smoothly varying $\tau(\omega)$. The choice of the filters $H(\omega - \omega^H)$ for surface waves must satisfy two conditions: no phase distortion (H must be real) and the best resolution. The optimal choice is a Gaussian filter, with central frequency ω^H and width of frequency band β :

$$H(\omega) = \frac{1}{\sqrt{2\pi}\beta} e^{-\frac{(\omega - \omega^H)^2}{2\beta^2}}$$

The bandwidth β of the optimal filter is inversely proportional to the source-receiver distance. The combination of all so filtered signals is a complex function of two variables, ω^H and t :

$$S(\omega^H, t) = \int_{-\infty}^{+\infty} H(\omega - \omega^H) K(\omega) e^{i\omega t} d\omega \quad (11)$$

The function $S(\omega^H, t)$ is called frequency-time representation of a signal and abbreviated as FTAN (Frequency-Time Analysis) (Levshin et al., 1972).

A contour map of $|S(\omega^H, t)|$ is called FTAN map and, for ω fixed, it represents the signal envelope at the output of the relevant filter. For this reason, to each input signal will correspond a ‘mountain ridge’ (increased values) in the FTAN map extending along the dispersion curve $t_m(\omega^H)=\tau(\omega^H)$, being t_m the arrival time of $|S(\omega^H, t)|$ maximum at the central frequency ω^H .

The frequency- time region of a signal is that part of the (ω^H, t) plane occupied by the relevant crest (Fig. 25). The statement that in the (ω^H, t) plane ‘the energy of a signal concentrates around its dispersion curve’ acquires a definite meaning in terms of $|S(\omega^H, t)|$. An automatic search of the group time $\tau(\omega_i)$ corresponding to the maximum of $|S(\omega_i, t)|$ is done for each ω_i , resulting in a group time curve with frequency shown on the FTAN map. Being known the source- receiver distance, the group time $\tau(\omega_i)$ is transformed in group velocity (Fig. 25, from Nunziata C. 2005).

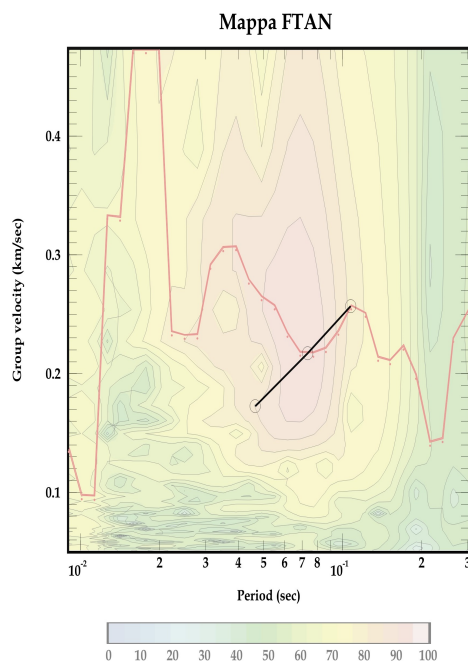


Fig. 25 – FTAN map computed for the recorded signal (Fig. 24): $|S(\omega^H, t)|$

In Fig 25 amplitudes, expressed in dB, are shown with different colours. The red line is the dispersion curve passing through energy maximum at each period.

The black line is the choice by the investigator.

The function $S(\omega^H, t)$ is not a property of the original signal alone, but also involves the filter characteristics $H(\omega - \omega^H)$ chosen by the investigator. Different choices of $H(\omega - \omega^H)$ will transform the same signal to different $S(\omega^H, t)$ functions.

The next step of the dispersed signal analysis must provide the signal identification and the separation of the signal from noise. FTAN method uses the linear filtering method, that is a transformation whose parameters are invariant under a time shift (frequency filtering). Such filtering procedure should separate, without distortion as far as possible, the part of the plane in which the signal frequency-time region lies (Fig. 26).

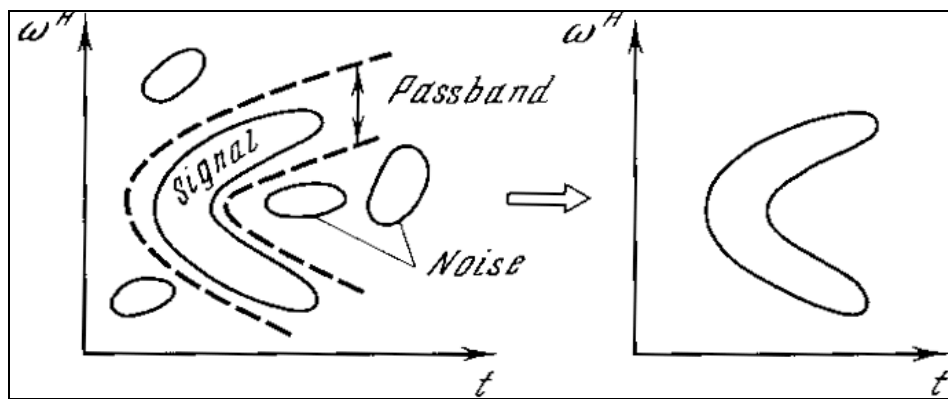


Fig. 26 – Representation of a floating filter in action.

This operation can be imagined as a ‘frequency filter whose parameters vary in time’, that is the filter band is ‘floating’ along the dispersion curve. As the signal energy is concentrated along the dispersion curve, it is not significantly distorted, while the noise outside the dispersion curve does not pass through a floating filter (Fig. 27).

The most important thing in a floating filter is phase equalization. If we approximately know the dispersion curve of a signal (denoted $\hat{\tau}(\omega)$) from FTAN results, subtracting from the filtered signals the phase computed from $\hat{\tau}(\omega)$ (by an integration operation), we make the signal weakly dispersed and the envelope of the amplitudes is a narrow peak. Such operation has the only

effect to alter the initial phase of the resulting signal and shifting it to a convenient instant of time, for example, to the midpoint of the record. The recovering of the original signal shape is obtained if we use the inverse procedure of phase equalization, that is by adding the same function to the signal phase spectrum.

The procedure of floating filtering thus consists in four steps as shown in the resulting FTAN maps (Fig. 27).

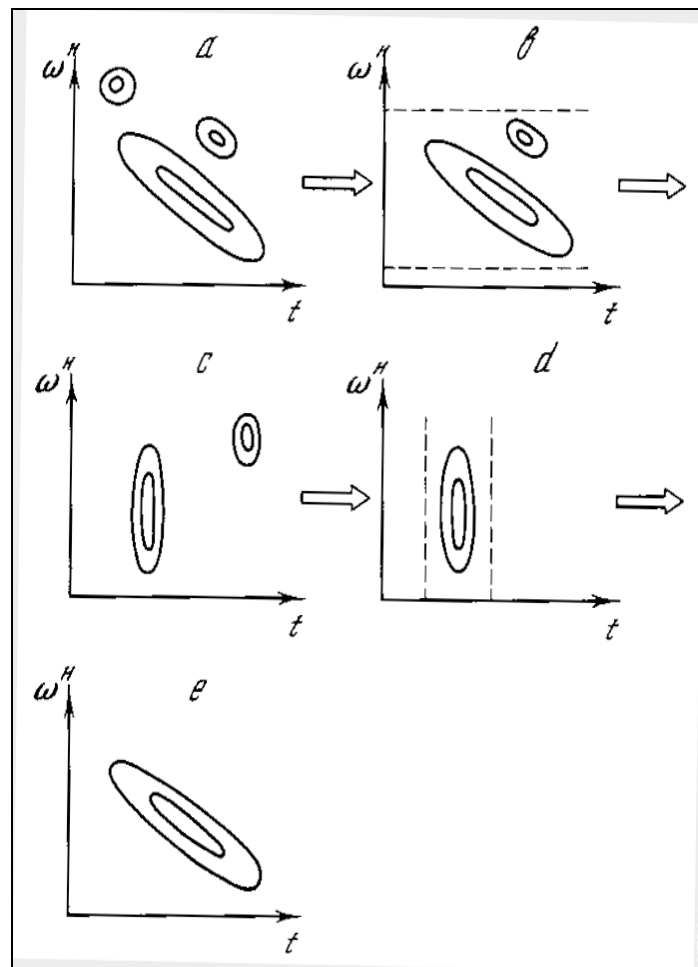


Fig. 27 – Scheme of a floating filter, see text for details

Floating Filter steps of scheme in Fig. 27:

- 1) FTAN map of the original signal.
- 2) Bandpass filtering.
- 3) Phase equalization: the effect in the time domain is to transform a dispersed signal to a short pulse signal
- 4) Time window;
- 5) Inverse phase transformation. The record assumes the original form, but the noise has been completely eliminated.

Lastly, we can repeat FTAN analysis on the resulting signal (Fig. 29) and go back to time domain with a signal only containing the fundamental mode (Fig. 30).

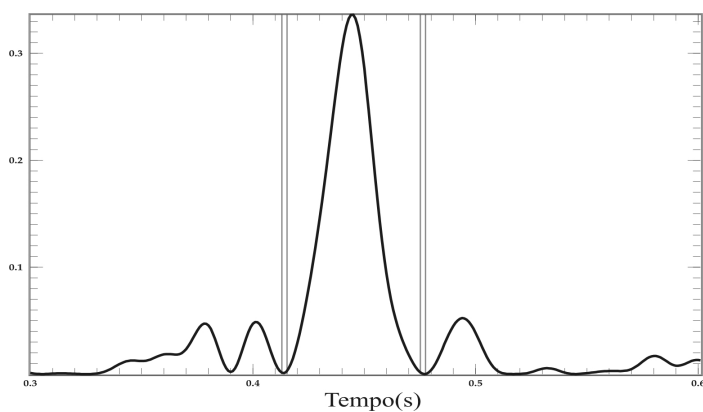


Fig. 28 – Result of phase equalization in the time domain on the recorded signal (Fig. 24)

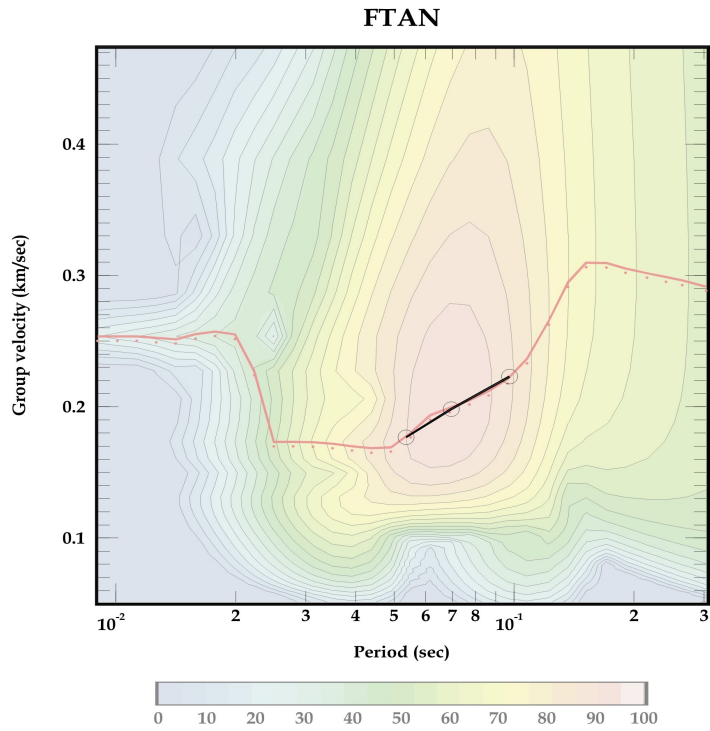


Fig. 29 – Final FTAN map with the fundamental mode extracted from the recorded signal (shown in Fig.24) from Nunziata C. (2005).

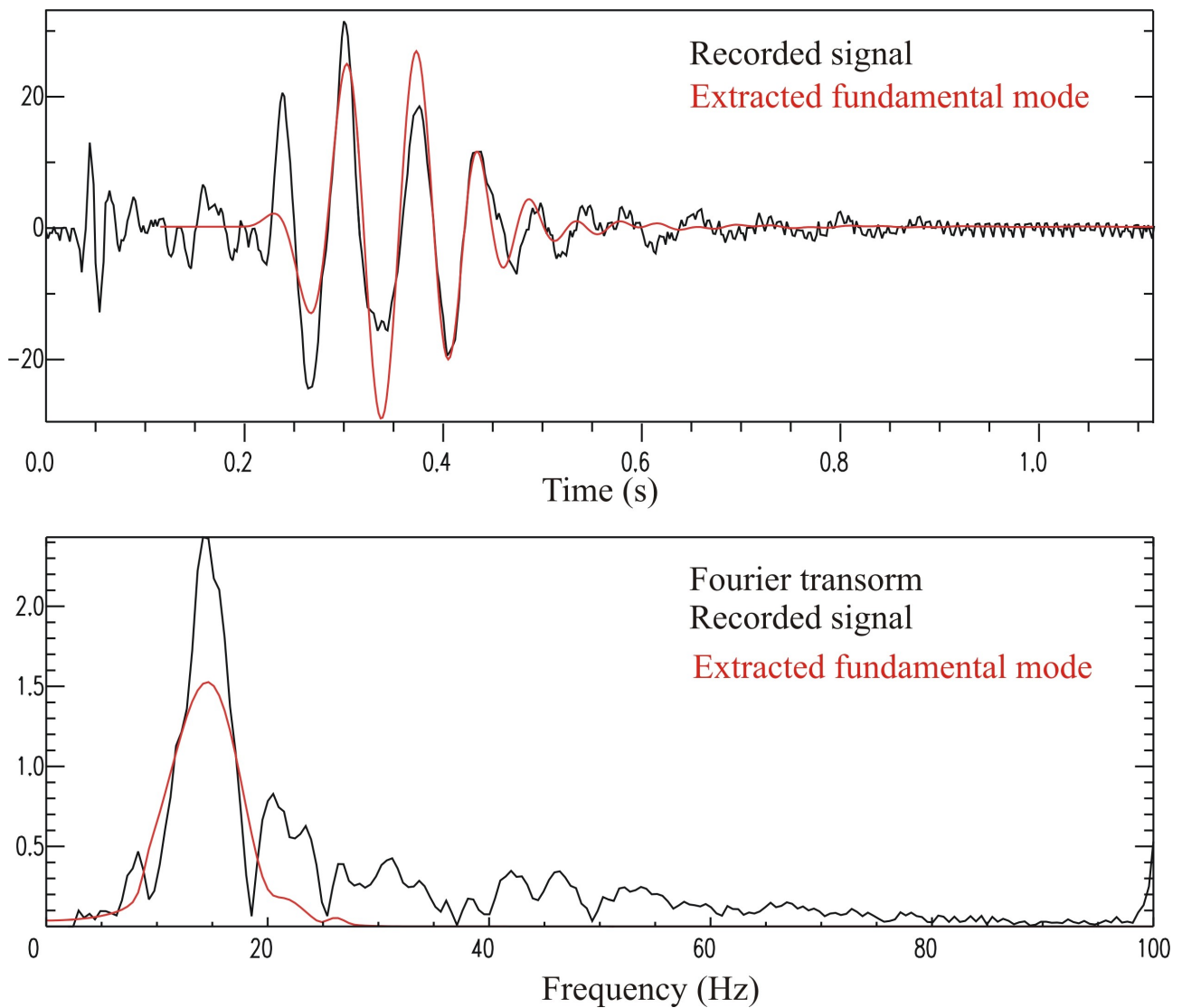


Fig. 30 – Fourier spectra of recorded and extracted fundamental mode signals.

4.2.2 Inversion and direct modelling

This work (see chap 4.3) mainly concerns direct modelling, but only non linear inversion could reach detailed Vs profiles. As explained to infer Vs model from dispersion curve we can use a direct model (trial and error) or an inversion.

An average dispersion curve of Rayleigh group velocities with errors is then computed from FTAN analysis on a signal, which can be inverted to determine S-wave velocity profiles versus depth. A non-linear inversion is made with the hedgehog method (Valyus et al., 1969; Panza, 1981) that is an optimized Monte Carlo non-linear search of velocity-depth distributions. In the inversion, the unknown Earth model is replaced by a set of parameters and the definition of the

structure is reduced to the determination of the numerical values of these parameters. In the elastic approximation, the structure is modelled as a stack of N homogeneous isotropic layers, each one defined by four parameters: V_p , V_s , density and thickness. Each parameter can be fixed (during the inversion the parameter is held constant accordingly to independent geophysical evidences — the a priori information), independent (the variable parameters that can be well resolved by the data) or dependent (the parameter has a fixed relationship with an independent parameter).

In the inversion problem of V_s modelling, the parameter function is the dispersion curve of group velocities of Rayleigh fundamental mode. Depending on the error of the experimental group velocity data, it is possible to compute the resolution of the parameters (Panza, 1981). Lower is the experimental error, better is the resolution of inverted parameters. The estimation of the resolution of a parameter gives the 'weight' of that parameter in the resulting earth model, hence all parameters with low resolution must be excluded as the experimental function of parameters is negligibly influenced by them. Changing some of the model parameters at a time in a systematic manner, phase or/and group velocities are computed. These theoretical velocities are then compared with the corresponding experimental ones. If the root mean square error of the entire data set is less than a value defined a priori on the basis of the quality of the data and if, at a given frequency, no individual computed velocity differs from its experimental counterpart by more than an assigned error, depending upon the accuracy of the measurements, the model is accepted as a solution. From the set of solutions, we accept as representative solution or the one with rms (root mean square) error closest to the average rms error of the solution set (to reduce the projection of possible systematic errors -Panza, 1981- into the structural model) or the one corresponding to available geological information.

4.3 XFTAN Software

The Ftan technique explained lacked of commercial, or better friendly- use, software. Many correlated features that involves Ftan analysis not are besides comprehended in the FTAN software package. In other terms this powerful methodology, that permits the surface wave dispersion estimation, did not have an adequate software update.

For this reasons the Seismological Group of Prof. G.F. Panza of the University of Triest, developed a new FTAN software, revolutionary for the common geophysicists users. Dr. F. Vaccari, under the supervision of the Prof. G.F. Panza, created XFTAN, that combine the rigorous signal treatment with useful graphic solution and many added features.

The XFTAN permits a clear and rapid visualisation of the original signal, in time and frequency domain. As input it is possible to use SAC or ASCII file. The operator can easily computes the FTAN Map, modifies the map output choosing the period and the velocity investigated, the filtering applied, and to set log or normal axes. Pointing in the map the Frequency/period, the velocity and the LAMBDA/2 of the pointer position are directly showed. The operator can visualize absolute or relative maxima (in Db), and it is possible draw the dispersion curve having his interpolation. The important step of choosing dispersion is greatly simplified selecting the part of map considered related to the Rayleigh dispersion, and selecting the operator 'filter'. The filtered area is directly overlaying the original signal, so the operator can directly test his choose and overly other filter in different colours. This is a fundamental upgrade of Ftan original code.

Running XFTAN (Fig 31), a significant part of the screen, that represent the strongest innovation, is dedicated to the first direct structural modelling. The operator can select a 1d layered model (Thickness, density, Vp and Vs), calculate the synthetic dispersion with the Modal Summation Technique (G.F. Panza 1985) and plot the fundamental or higher mode of Rayleigh wave directly on FTAN map. In addition the software compute the partial derivatives of the structure (PANZA 1981). Selecting a particular frequency of exploration interested, a graphic shows the structure selected, and the computed derivatives explaining which part of structure are correlated to the frequency. This represent a quick and easy first

direct modelling, often sufficient for many operators needs (e.g Vs30 classification).

The author support to XFTAN software consist mainly in his massive test on experimental signal, and the relatives suggestions. Hundred of signals are recorded in the north Italy area, the XFTAN is applied comparing the resulting shear waves definition with the known lithology of the subsoil. Every bug occurred was rapidly resolved by software developers.

XFTAN was widely applied in this work. It was applied e.g. to Earthquakes records, follow his seismological most frequent use in scientists community. We also computed the dispersion curve of controlled source signals (Seismic Gun, Industrial hammer, TNT), in order to infer the upper structural model (VS30). XFTAN was used to analyse the Green Function obtained by noise treatment, as tool for investigation of deeper structure. We found extremely useful the direct modelling based on the synthetics computation of Rayleigh mode. We tested our experimental data comparing them with synthetic ones. For these kinds of subsoil investigations, without high accuracy requesting (e.g. big area seismic hazard evaluation) this software features seem adequate and successful.

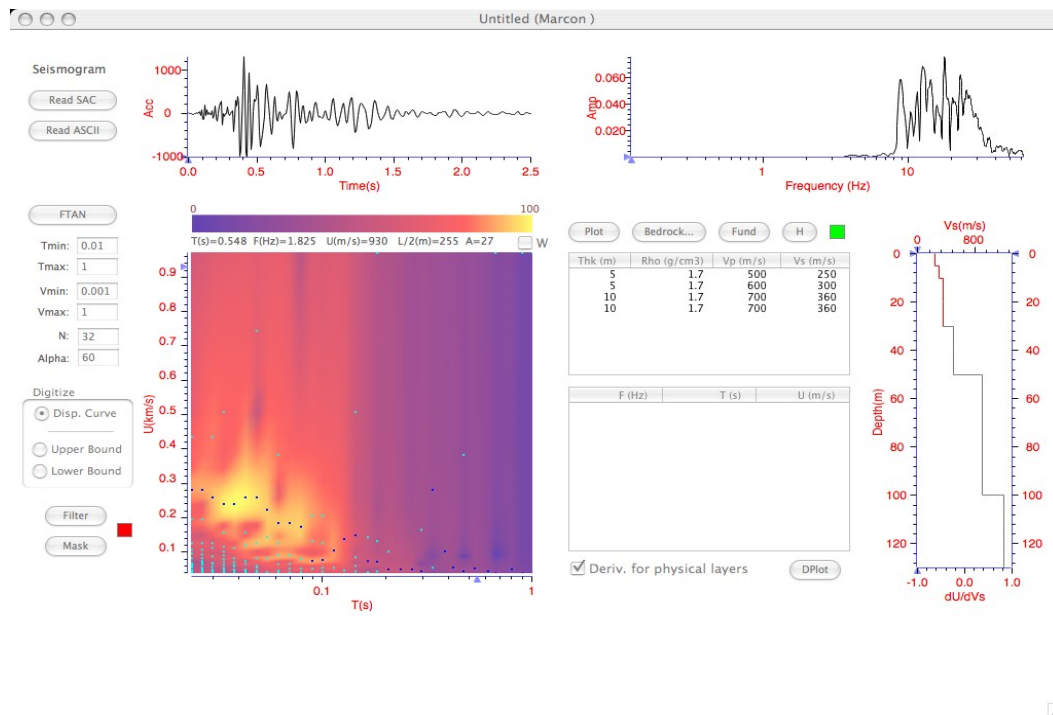


Fig.31 XFTAN software screenshot

4.4 Upper Shear wave of studied area

It has long been recognized that shear wave velocity (V_s) plays a fundamental role in the ground motion amplification and is, in fact, included in the seismic building codes. The recent Italian seismic building code (3274 Law) defines the seismic action for different categories of foundation soils based on different V_{s30} , average seismic shear velocities to 30 m of depth computed as:

$$V_{s30} = \frac{30}{\sum_{i=1,N} \frac{h_i}{V_i}} \quad (12)$$

Being h_i and V_i , respectively, thickness and velocity V_s of i -layer and N the total number of layers.

We designed to evaluate the V_{s30} Values for 3 main sites of the studied area. We use a single station digital sensor with 256 Hz sampling and 24bit dynamic (natural frequency of 1Hz). Several types of seismic sources have been used in order to reach deeper structure.

The 3 main measurements Points:

- Malafesta
01257.7107 °Long E
4549.7505 °Lat N
- S. Michele al Tagliamento
01259.4037 °Long E
4545.8003 °Lat N
- Bibione
1304.0737 °Long E
4539.2661 °Lat N

The source- receiver offset varied from 50 up to 100 m, the impulsive sources were obviously repeated in order to increase signal/noise ratio.

The source used for the 3 sites are:

- 20 shot with heavy hammer of 700 Kg in free fall from 1.5 m
- 10 shot with hammer of 10 kg
- 6 shot with cal.8 seismic gun

The figures below show the XFTAN maps of representative signals of the three sites.

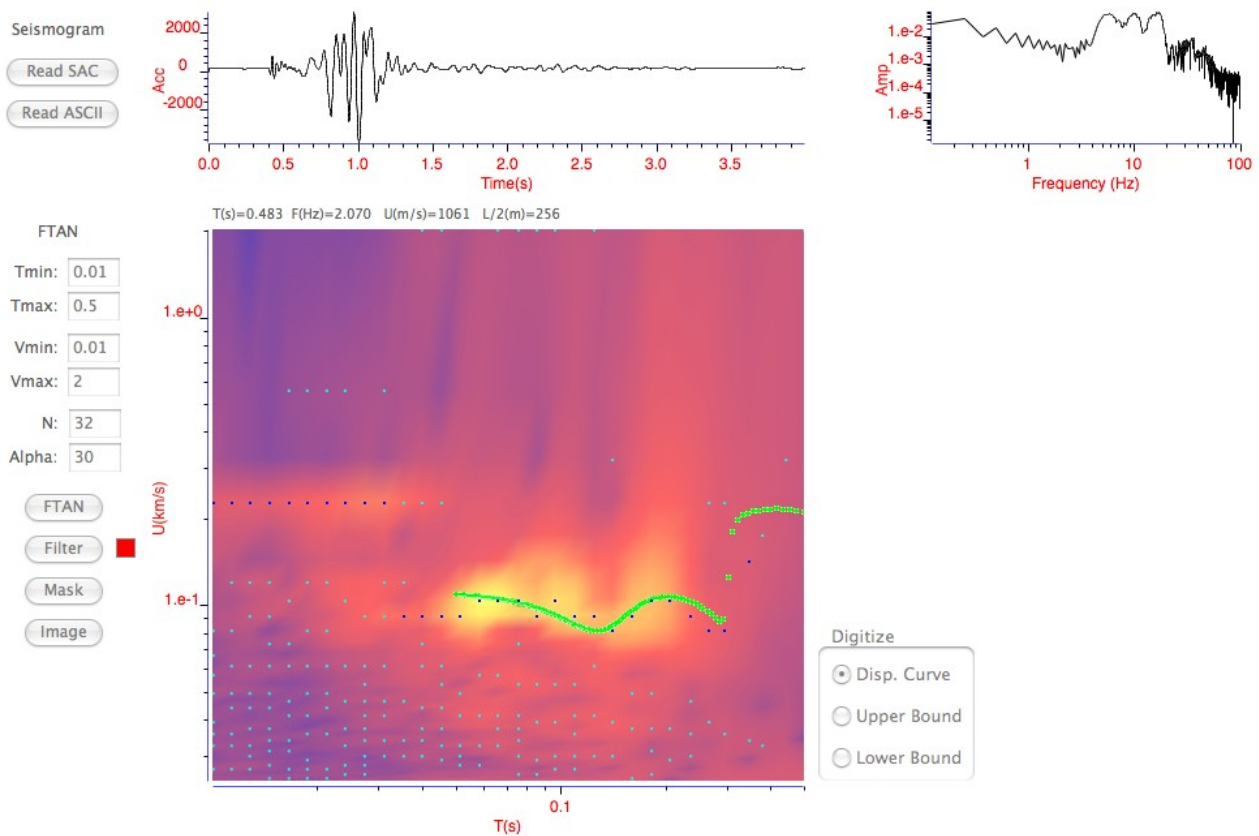


Fig.31 XFTAN map of Malafesta site, at the top the signal recorded and his FFT, in green the synthetic dispersion curve of the chosen structural model

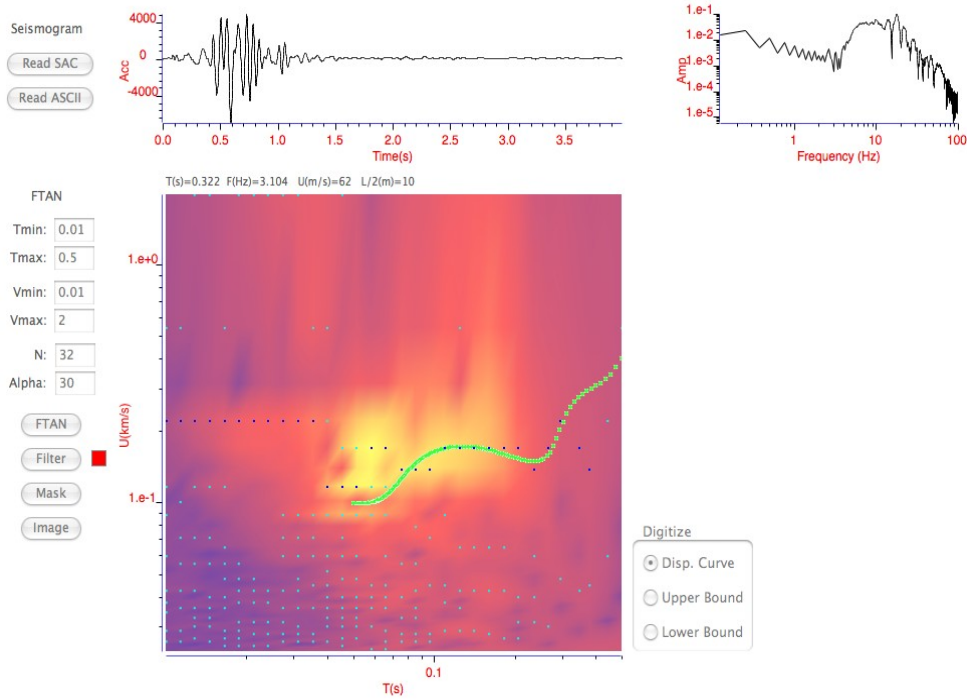


Fig.32 XFTAN map of S.Michele site, at the top the signal recorded and his FFT, in green the synthetic dispersion curve of the chosen structural model

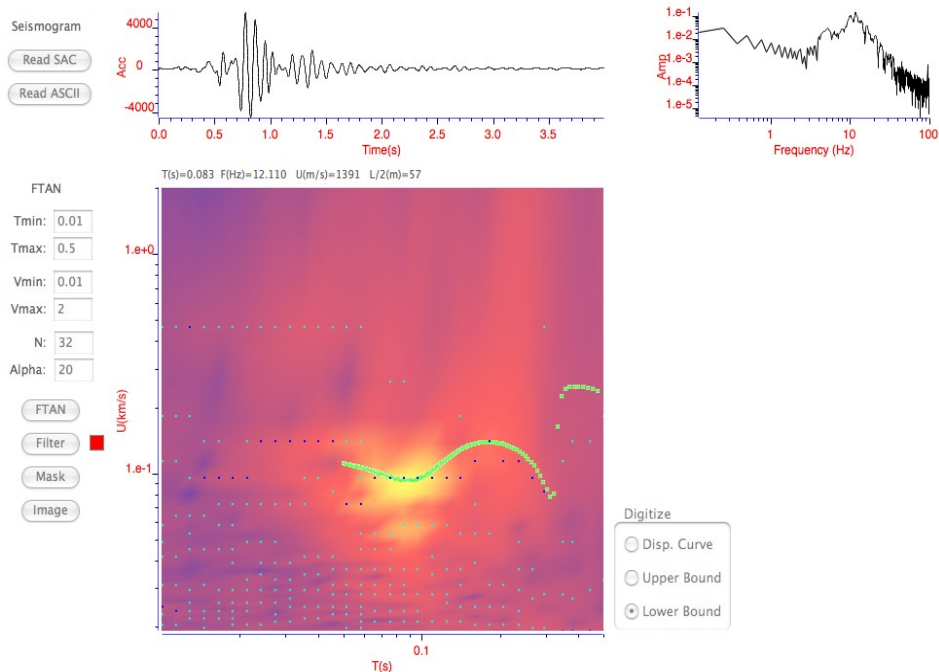


Fig.33 XFTAN map of Bibione site, at the top the signal recorded and his FFT, in green the synthetic dispersion curve of the chosen structural model

Main Vs30 values obtained and Italian classification are in Tab1. Ec8 classification is in Tab2.

Location	Vs30	Subsoil Class
Malafesta	188 m/s	C
S.Michele al Tagliamento	270 m/s	C
Bibione	170 m/s	D

Tab1 Vs30 Obtained

Subsoil class	Description of stratigraphic profile	Parameters		
		$V_{s,30}$ (m/s)	N_{SPT} (bl/30cm)	c_u (kPa)
A	Rock or other rock- like geological formation, including at most 5 m of weaker material at the surface	800	–	–
B	Deposits of very dense sand, gravel, or very stiff clay, at least several tens of m in thickness, characterised by a gradual increase of mechanical properties with depth	360 – 800	50	250
C	Deep deposits of dense or medium- dense sand, gravel or stiff clay with thickness from several tens to many hundreds of m	180 – 360	15 - 50	70 - 250
D	Deposits of loose- to- medium cohesionless soil (with or without some soft cohesive layers), or of predominantly soft- to- firm cohesive soil	180	15	70
E	A soil profile consisting of a surface alluvium layer with $V_{s,30}$ values of class C or D and thickness varying between about 5 m and 20 m, underlain by stiffer material with $V_{s,30} > 800$ m/s			
S ₁	Deposits consisting – or containing a layer at least 10 m thick – of soft clays/silts with high plasticity index (PI 40) and high water content	100 (indicatively)	–	10 - 20
S ₂	Deposits of liquefiable soils, of sensitive clays, or any other soil profile not included in classes A –E or S ₁			

TAB 2 Ec8 Soil 'Classification of subsoil conditions

4.5 XFTAN on Earthquakes

The FTAN methodology, as explained, has an intensive application on earth seismic exploration. The aim of this study is apply passive and controlled source seismic prospecting in order to define a realistic structural model of the studied area. We applied also the FTAN methodology to the local earthquakes acquired during the 6 months of recording period. The event occurred could be considered too far for the local purpose of model definition. In fact, applying FTAN (or any other earthquake single station analysis) to the single station receiver signal, we get a 1D structural model between source and receiver. This kind of methodology finds strong limitations in our specific geological conditions.

The Carbonatic Friuli Platform, as explained in chap.1, rises toward the north direction, and emerge in the pre- alp region. The northern zone, epicentre of the earthquakes studied, lack of sedimentary cover, that grows toward coastline and characterized our studied zone. Along the path between source and receiver (circa 100km), the seismic waves, in the first 500m of subsoil, pass from hard bedrock (as Cretaceous and Miocene formations) to clay sediments.

From the seismological point of view, the relevant data is characterized the sediments body (first 500m) of our studied area. The average value we get, applying Frequency Time Analysis to the higher frequencies related to the upper structural model, is useless for sediments characterisation. We estimated, instead, the shear wave velocities of the rock formation (e.g Cavanella Formation), in very good agreements with the P velocities used by AGIP seismic prospection (Tab 3).

Geological Age	ROCK Description	Vp m/s
Miocene	Vittorio Veneto Sandstone	3000- 3500
Miocene	Conglomerates	4000- 5000
Miocene	<u>Cavanella formation</u>	4000
Miocene	Flysch	3500

Tab3 Vp velocities assumed in AGIP deep seismic reflection prospecting

As figures 34 show below, for the frequency band consider, we get information about the Rayleigh Group Velocity of deep structure. We can evaluate velocities of bedrock formation as the Cavanella Formation and the Miocene sandstone. For Cavanella a Shear wave of 2500 m/s appear in good agreement with the 4000 m/s of compressional wave found by reflection past seismic experiments. For the Miocene Sandstone we consider that shear velocity of 2000 m/s is consistent with the 3500 m/s compressional wave suggest by hydrocarbon past research prospecting.

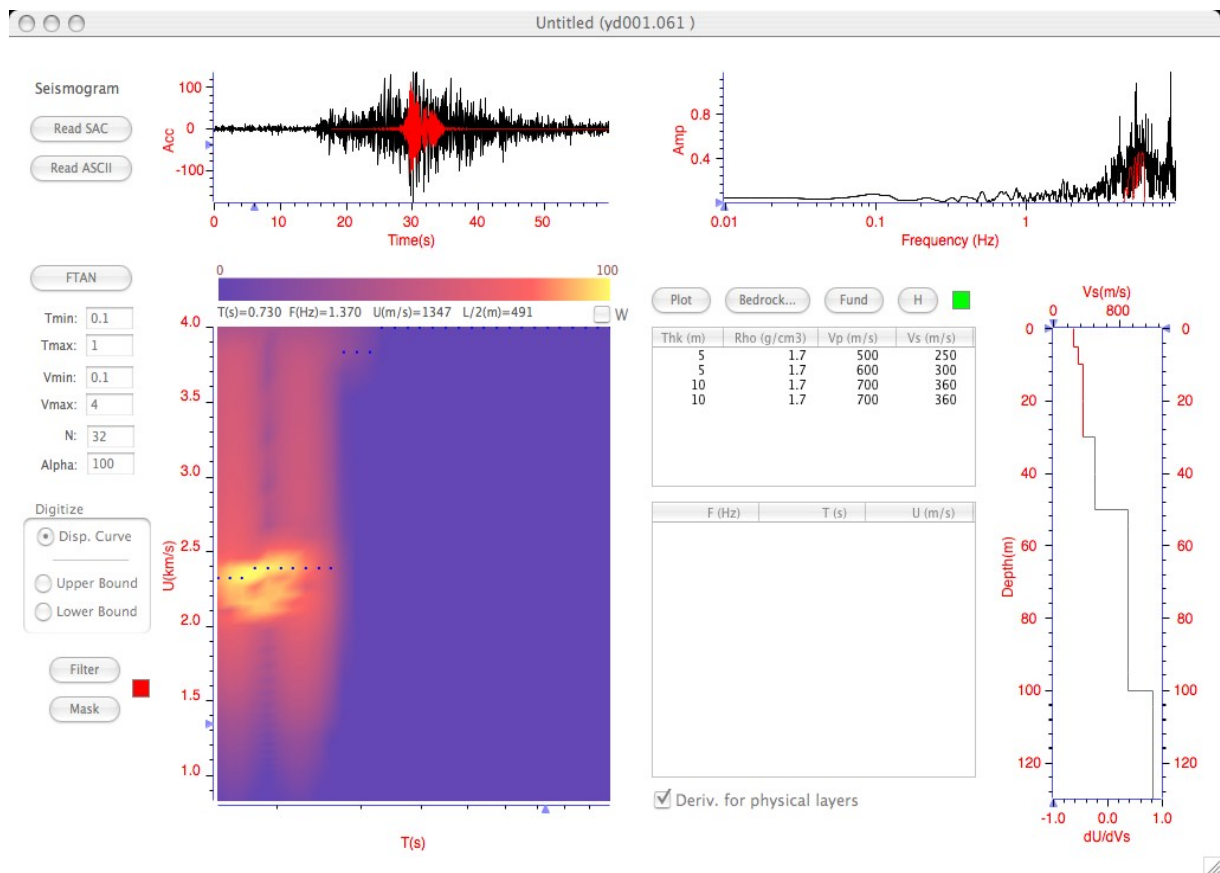


Fig.34 XFTAN map of Gemona Earthquake. At top recorded signal and his FFT, in red Rayleigh fundamental mode extracted by Ftan

4.6 Attenuation Test

During October 2006, thanks to the cooperation with the 'Questura di Padova', we exploded 30Kg of TNT in the Tagliamento bed, in Morsano al Tagliamento (FIG.35,36). The aim of the experiment was to evaluate difference in the attenuation along N-S and E-W directions.

We used 8 mobile station, 5 along the N-S direction, and 3 along the perpendicular E-W one. We fixed the 5 stations along N-S direction, considering the logistic installation problem, at 1.5 Km, 2.7 km, 5 km, 6 km and 9 km from the source. Along the E-W direction the 3 stations were at 3 km, 5 km and 7 km from the source.

The TNT was buried only few meters under the river gravel, cause to the presence of shallow water due to the high river carry. For this reason, the amount of Energy, as explained in Figure 37 , decreased more rapidly than deigned. Only the stations closer the explosion has a relevant signal/noise ratio.



Fig 35 and Fig.36: TNT buried in Tagliamento bed

The attenuation study reveals an anisotropy in the energy distribution, due probably to different sediments deposition. The N-S direction present less energy attenuation than the E-W one. This result was attended, considering the rivers energy of deposition, mainly directed toward South direction. The E-W direction appears as perpendicular to the main axes of past and recent river beds, and is characterized by fining sediments. Due to the shallow depth of source explosion, only upper sediments are reached by seismic energy, underlining this difference. At 3 km from explosion, the amount of energy that reached the first E-W station is clearly less than the N-S one, and it is explained by the sediments nature.

The aim of the TNT project wasn't the active seismic prospecting or study of surface wave dispersion. The station were gps-time synchronized but the explosion wasn't triggered due to logistic problems.

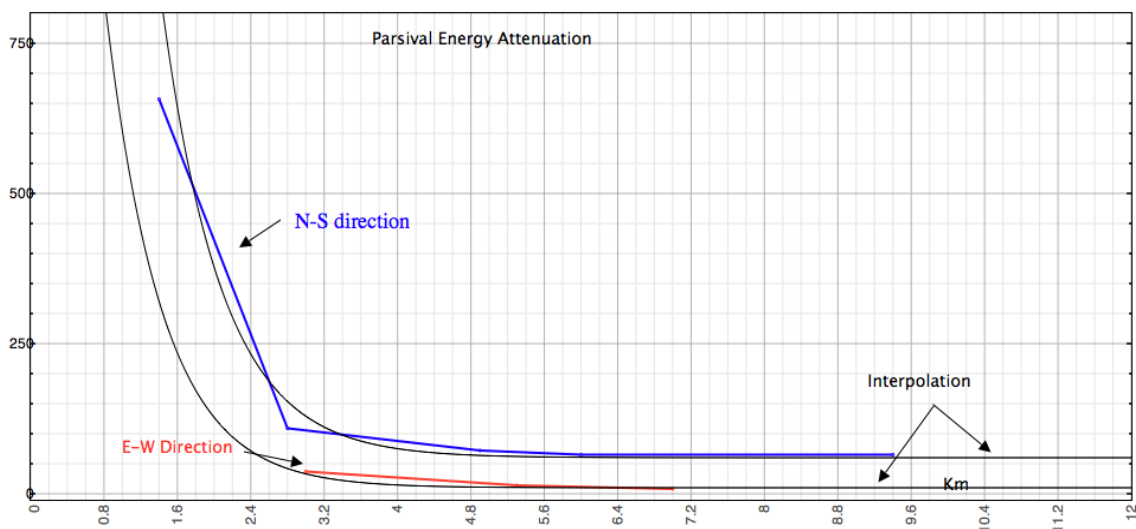


Fig.37 Energy Attenuation of TNT explosion, in Blue along N-S direction, in red along E-W direction.

4.7 Source Comparison

The study on the field was used even for seismic sources comparison. To reach 40 m depth of investigation we need a low frequency receiver, but also a good source able to be strong enough and, above all, that reaches low frequencies. The receiver, for the intrinsic problem of the wavelength involved, must have 1 Hz natural frequency to obtain a good response in low frequencies.

Fig.38 shows a comparison of 3 sources (100m offset) in the same site test: 30g TNT (buried at 50 cm, 2 shots), seismic gun and 8kg hammer.

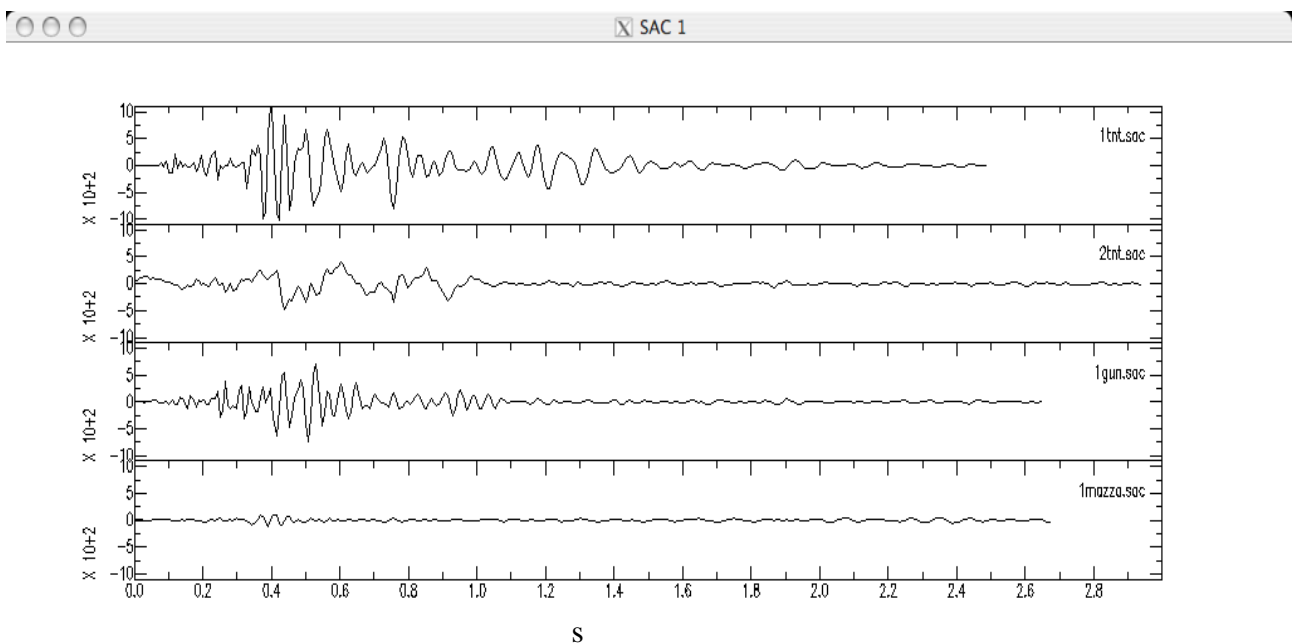


Fig.38 Sources comparison (from top): 30g TNT, 30g TNT (noising), Seismic Gun and 8 Kg Hummer. Same Amplitude axes.

As evident, a simple hammer has sensible lower energy than little explosions, and the signal to noise ratio is quite small at 100 m distance.

Studying Rayleigh dispersion in depth we need even low frequency in our signal. Fig, 39 and 40 reports FFT of cal.8 seismic Gun (third signal of fig.38) and and the FFT of 8kg hammer shot (bottom in fig,38).

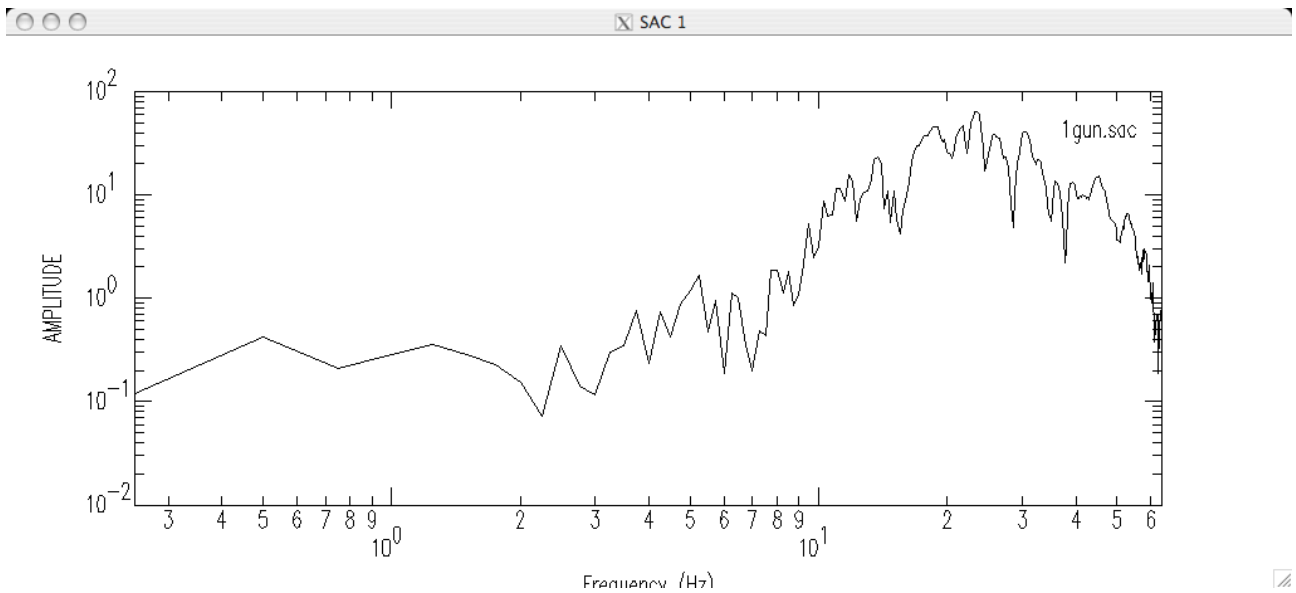


Fig.39 FFT of cal,8 seismic gun exploded at 100m distance

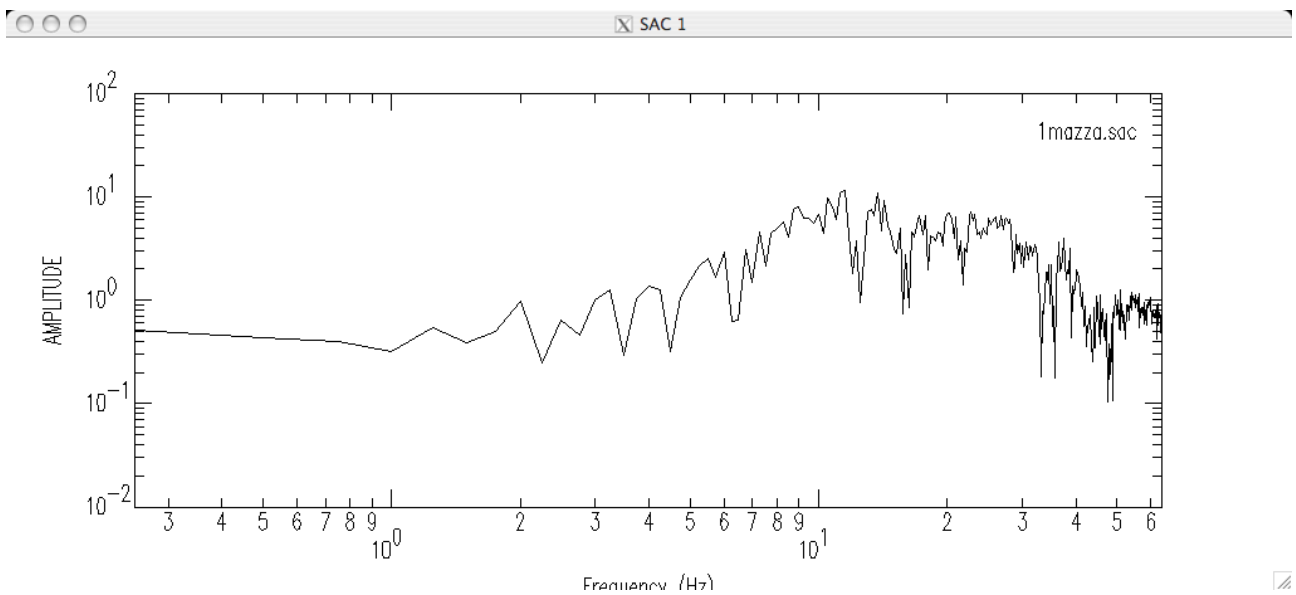


Fig.40 FFT of 8kg hammer at 100m distance

As clearly visible, in the frequency range commonly important for surface wave dispersion upper subsoil study (few Hz), the energy of the hammer are 1 order degree less (note y axes is log scale).

This implies is very hard to explore 30-40 m depth with common refraction equipment (light hammer and 14 Hz vertical geophones), especially in case of low velocities sediments. Our experiments, involving low velocities sediments, demonstrated that the so called 'Seismic gun' represent a good power/portability solution. Our instrument is a cal. 8 seismic gun that shots at ca 50cm depth. The user stay on an heavy steel plate, to contrast shot energy.

The limitations explained involve obviously all the methodologies based on surface wave dispersion, not only the FTAN analysis. A source able to reach low frequency and a good signal to noise ratio at 100- 130 m, and obviously good low frequency receivers, are behove for Vs30 soil classification.

Chap.5
Experimental Activities
Cross Correlation of seismic noise

5.1 Time Cross- Correlation of seismic Noise

Cross- correlation of noise recordings can be used to infer the impulse response between receivers. Many works have been performed on this topic in the past few years in various fields of wave physics such as ultrasonics [Weaver and Lobkis, 2001, 2004], underwater acoustics [Roux et al., 2004] and geophysics [Rickett and Claerbout, 1999; Campillo and Paul, 2003; Shapiro and Campillo, 2004; Wapenaar, 2004; Sabra et al., 2005a; Shapiro et al., 2005, Sabra et al.2005]. Despite the very different scales involved in ultrasonics (wavelength mm) compared to geophysics (wave- length of km), the basic physics of the process is the same.

The impulse response between two receivers is derived from the part of the noise that remains coherent between them, even if, at first inspection, it is deeply buried into local incoherent noise. After cross correlating over a long time (for example, one month in [Sabra et al., 2005a; Shapiro et al ., 2005]), the noise correlation function (NCF) converges to the impulse response between the two receivers filtered by the bandwidth of the noise spectrum.

Usually the Time Domain Green's Function between two points is estimated from the measured response from an active controlled source or using seismic sources of opportunity. The controlled source way may give a good resolution of subsoil (like the FTAN method used in this work), but have the strong limitation of depth investigation, linked to the logistic problem of strong source like explosive (chap. 4). On the other hand the use of earthquakes in order to explore earth structure is the only way to reach great depth of investigation, but have several limitations:

-we must wait the right local event for our purposes (and it could be a very long time in low seismicity areas)

-the part of the crust explored will always refer to the structure between the source and the receiver (and often the path is too long for the precision we need for the definition of the seismic scenario)

To reach a good depth investigation, since 1960, many methodologies based on seismic noise were developed. The noise (chap.3) is everywhere and always present. It contains a large frequency range, and above all, it contains low frequency contribute (below 1 Hz), that can be used to reach deeper structure.

As we explained in Chap 3, the most used methodologies are passive noise array (SPAC method, f-k method etc.). One of the limit of this methods is the need of many stations, rather mobile and broadband, that means a great cost.

One of the most useful passive method, developed in this work, is the Time Cross- Correlation of seismic Noise. The possibility of estimating the fundamental mode Rayleigh wave Green functions, cross- correlating long noise sequences, is known since the works of Shapiro (2003), Sabra (2005) and Campillo (2003). The application of Noise Cross Correlation (NCF) in geophysics is relatively recent and is still under development. There are several data processing methodologies. In principle the data collected were reduced keeping only the sign of the signal (bit reduction, Campillo et al.2004). However, this rough clipping seems to create high frequency noise and artificially modifies the ambient noise spectrum. In recent works (Sabra et al 2006) prefer to remove from the noise just the strong transient, cutting data exceeded a value fixed on the base of standard deviation.

Another fundamental aspect is the directionality of seismic noise. We can distinguish an 'American school' (Roux, Sabra et al.), from the 'French school' (Campillo et al.). The former considers noise with a defined directivity, with recognizable signal only on one side of the Cross Correlation Function. This is linked to the ocean activity, predominant on California network recordings, that obviously generate a strong directionality of noise. This implies that we can recognize signal only on one side of the Cross Correlation (from Sea to inner land).

The 'French school' initially proposed works based on noise with directional preference (Stehly, Campillo and Shapiro 2004). Now they consider only diffuse noise field. In this condition we have to find the same signal in both parts of Cross Correlation (the positive and the negative one).

Based on our experience, we prefer to avoid bit reduction and we try to apply the Time cross-correlation even at a local scale, not using seismic stations with hundred of Km distance and months of recording like the works adduced. We used mobile broadband stations with inter-distance of few Km and time recording of hours or days. For the longer inter-distance and long time recording we focus on diffuse noise field, working with both parts of Noise Cross Correlation Function. For the short inter-distance experiments we were looking to higher frequency range, using anthropic source. In this case the noise directionality is not avoidable, and the signal is recognizable only in one part of NCF. We found however results in agreement with subsoil site knowledge.

We computed NCF between two mobile 3 components stations in North Venice Plain area. Then, we extracted the group velocities of surface waves with the Frequency-Time Analysis [Dziewonski et al. 1969; Levshin et al. 1972, 1992], for the purpose of determining a shear-wave velocity structural model.

Another aim of the study was to apply this methodology also for short station inter-distance and short acquisition time, in order to infer upper soil shear velocity. The results meet the seismic engineering needs, and are useful to seismic soil classification (e.g. Eurocode 8). Our conclusive purpose was to investigate the sediment deposits of the studied area, in order to define a realistic model of the subsoil useful for computing a deterministic seismic scenario.



Fig.41 S.Michele Test site Area. Stations Malafesta (M) and Bibione (B) (22Km inter-distance in yellow).

First we improve and test the method in 3 test- sites. The sites were selected for their experimental differences. The first test- site is near the Marco Polo Venice Airport (Tessera), in the Venice's plain 50km far from the studied area. The second site is in Alvisopoli village, very close to S.Michele al Tagliamento. The two sites have obviously different kind of seismic noise, particularly in term of directions of the sources. The third site was in the Venice Hinterland. Tessera Airport could be assumed as a strictly directional source, as we located the stations perpendicular to the airport runway. Venice is the third Italian airport with hundred of flights everyday, and we can assume it a constant noise source. The Alvisopoli test was made near the Triest- Venice Highway. The directionality of noise is obviously linked to these anthropic sources.

For these 2 sites we demonstrated that the well located source is suitable to define fundamental mode Rayleigh wave Green function we were looking for. The

signals extracted are clear, while often diffuse noise long array cross correlation are easy to misread.

5.2 Test Site Tessera

We installed 2 mobile 3- components receiver with high acquisition frequency range (0.1- 256Hz) with 128 Hz sampling and a/d converter of 24bit.

The 2 stations inter- distance is 1km and the distance between the airport runway and the closest station is 1.3 km. The N-S axe is disposed perpendicular to the coastline and to the airport runway. The recording time was 75 minutes. The time and the position accuracy was given by continuous GPS 4 satellites receiving.



Fig 42 Tessera Airport Area. Receiver are Red points.

Station 1	Station 2
Latitude: 45°30.7252 N	Latitude: 45°31.2049 N
Longitude: 012°19.8279 E	Longitude: 012°19.3966 E
Satellite no.: 04	Satellite no.: 04

We applied an undersampling code to the signals, reaching 20Hz sampling frequency. Then we removed the average to bypass instrumental characterisation. No strong transient events occurred during record time.

We performed the time cross-correlation of the signals recorded in the frequency range 0.5- 4Hz applying butterworth filters. We computed cross correlations with several time windowing to confirm the stability of the signal considered as the fundamental mode Rayleigh wave Green function.

The figure 43 shows the cross correlation results for vertical components. The signal was attended in the positive cross correlation path, correlating the nearest airport station as master. The arriving time of 3.8s was considered due to Rayleigh wave. The particle motion of the signal extracted is shown in Figure 44, it refer clearly to the retrograde elliptical Rayleigh wave motion.

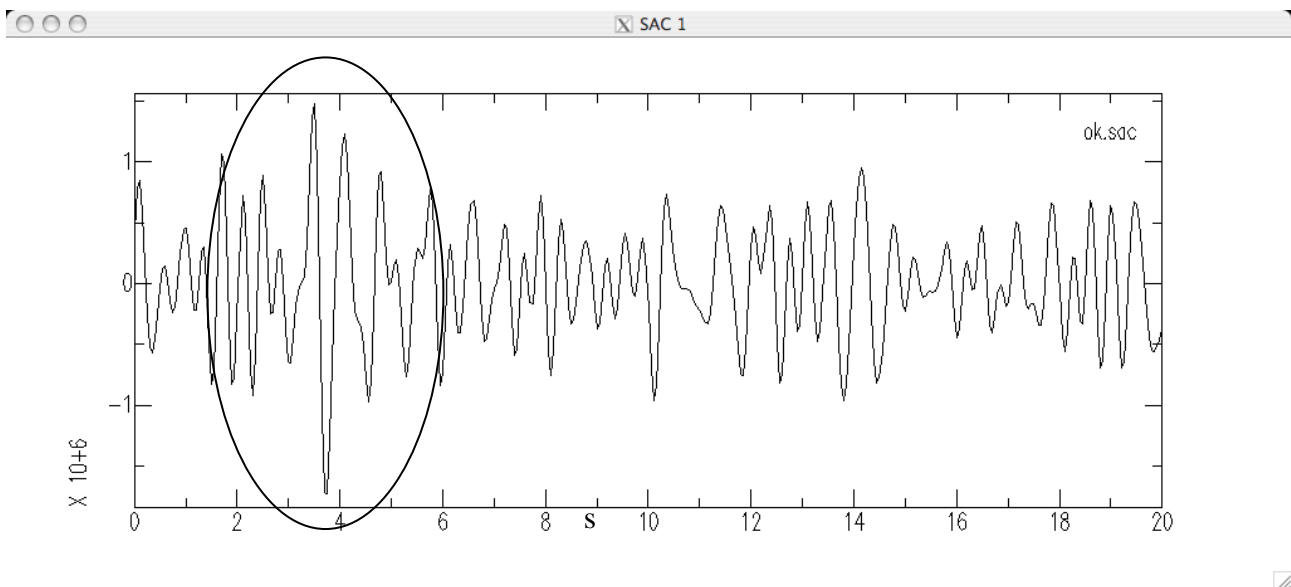


Fig 43: 20s NCF at Tessera. In oval signal considered as a Rayleigh arrival.

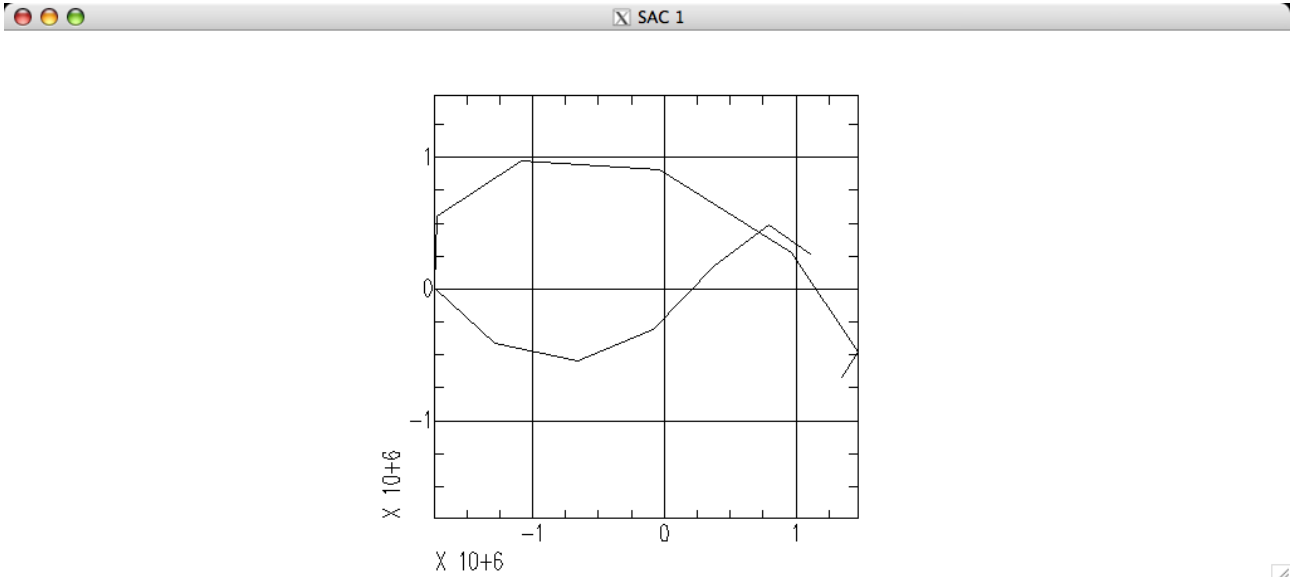


Fig 44 Particle motion (Z/R component) of signal considered as Rayleigh wave.

We applied the Frequency- Time analysis to the signal extracted (Fig.45). The Rayleigh wave dispersion curve inversion of the fundamental mode images a structure in very good agreement with the known lithology of the area (fig 46).

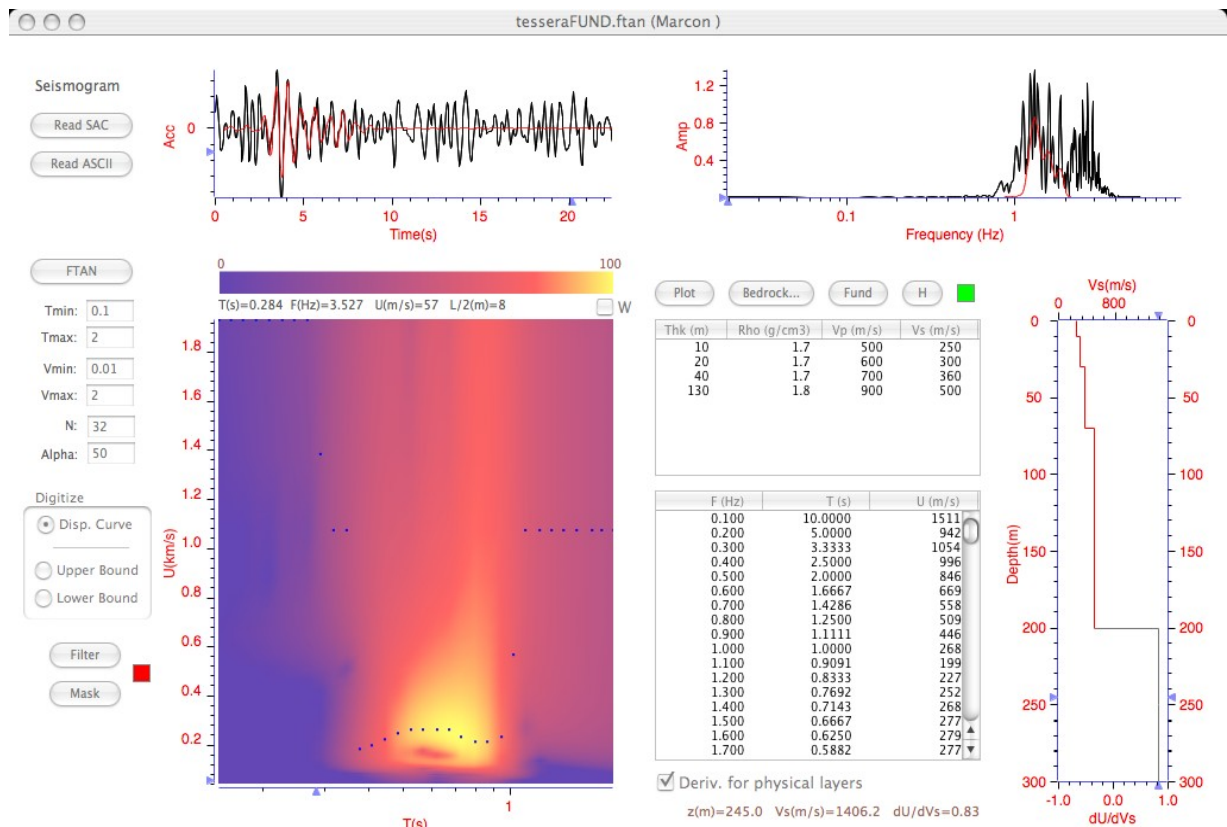


Fig 45 XFTAN Analysis of Signal in Fig 43. In red the signal extracted considered Rayleigh fundamental mode.

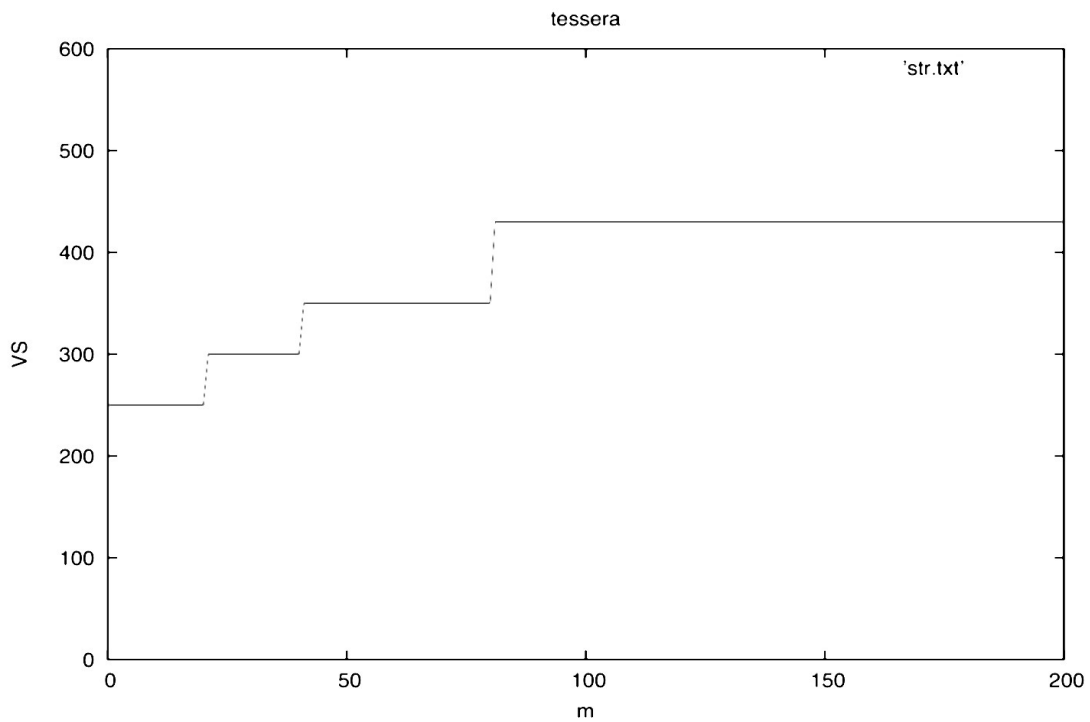


Fig.46 Vs structural model inferred for Tessera

Structure in Fig 46 was used to compute a synthetic signal. We computed Rayleigh fundamental mode for a point source with the modal summation technique (Panza, 1985). Fig 47 shows the comparison between the recorded signal and the synthetic one. The two signals are in very good agreement and confirm that we extracted Rayleigh fundamental mode.

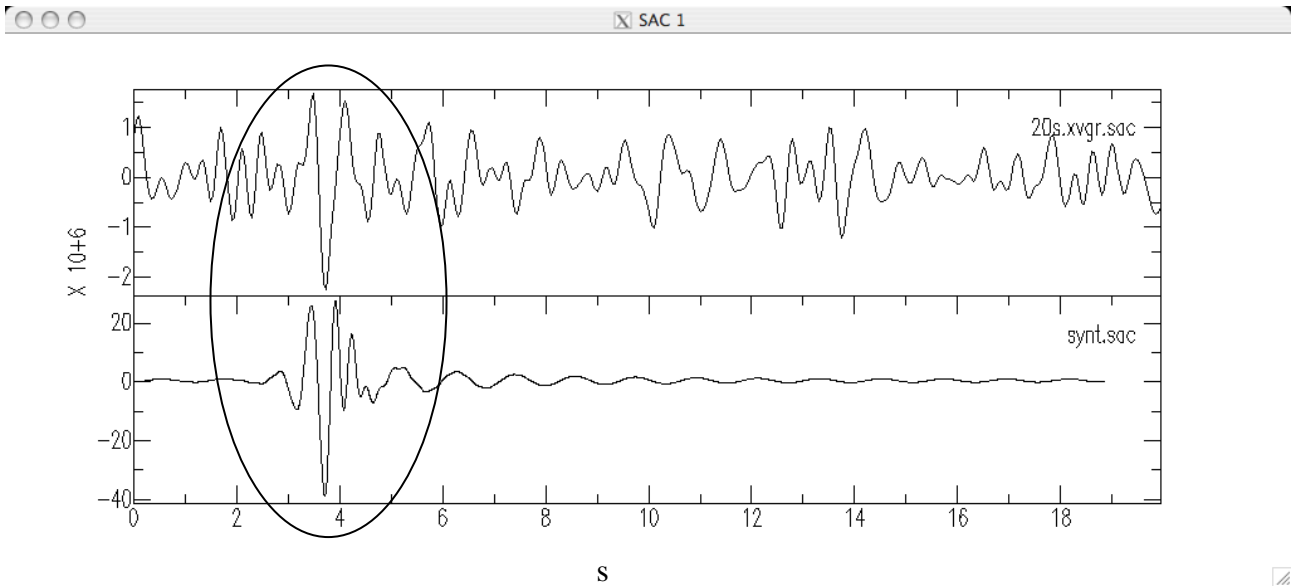


Fig. 47 Signal extracted (above) and synthetic (below)

This passive approach reached more than 150m of exploration depth. We consider it a great result in such lowland sediments. In fact, the common controlled source seismic prospecting suffer for the great amount of energy attenuation in this deposits.

The test site result, relatively close to the S.Michele al Tagliamento studied area, give however an important information about the sand- clay lowland sediments shear velocities.

5.3 Test site Alvisopoli

After the Tessera airport, we identified another possible noise source in the studied area: the Highway 'Venice-Trieste', that crosses the studied area in the Northern part. In order to avoid the noise contributions from the river Tagliamento, that flows in a perpendicular way to the highway, we installed 2 stations in Alvisopoli, 4.5 km far from the Tagliamento river. The station A was installed close the Highway, the station B 0.9 Km from the first, in the village Alvisopoli (Fig.48). The acquisition time was 75 minutes.



Fig.48 Alvisopoli Test Site. Stations in red.

Station 1	Station 2
Latitude: 45°48.3355 N	Latitude: 45°47.9758 N
Longitude: 012°55.0839 E	Longitude: 012°55.0687 E
Satellite no.: 04	Satellite no.: 04

The signal processing followed the same steps adopted for the Tessera site:

1. removing average,
2. pass band filtering between 0.5 Hz and 4Hz (butterworth), and

cross correlating with several time windows.

Figures 49 and 50 show the cross correlation between stations A (master) and B using, for the vertical component, time windows of 10s and 5s. It is clearly visible in both figures the signal around 3s, which is considered the surface wave time arrival. Fig.51 shows the particle motion computed using the same cross correlation of radial components. Fig.55 is the particle motion of the synthetic signal. They confirm the elliptical motion attended.

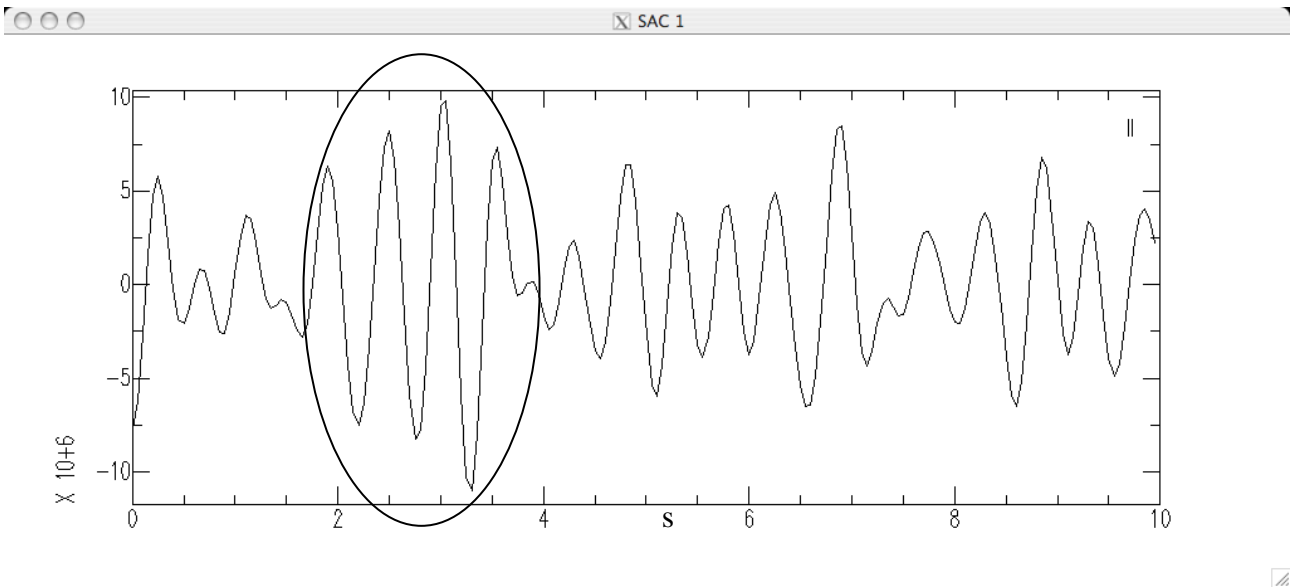


Fig 49 NCF of Alvisopoli for 10s time windowing

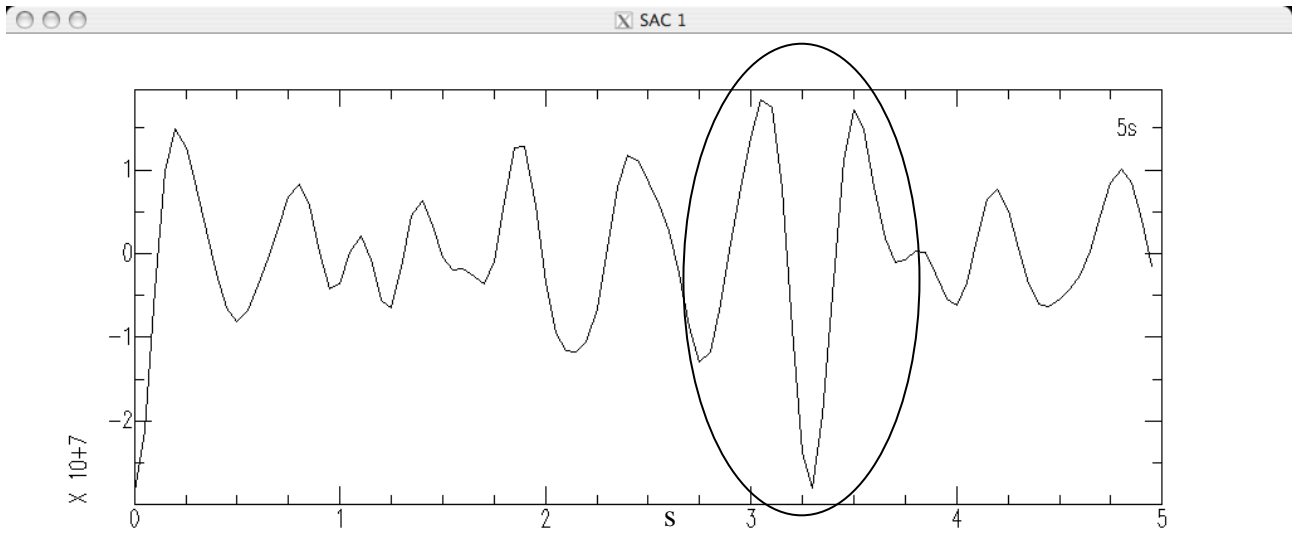


Fig 50 NCF of Alvisopoli for 5s time windowing

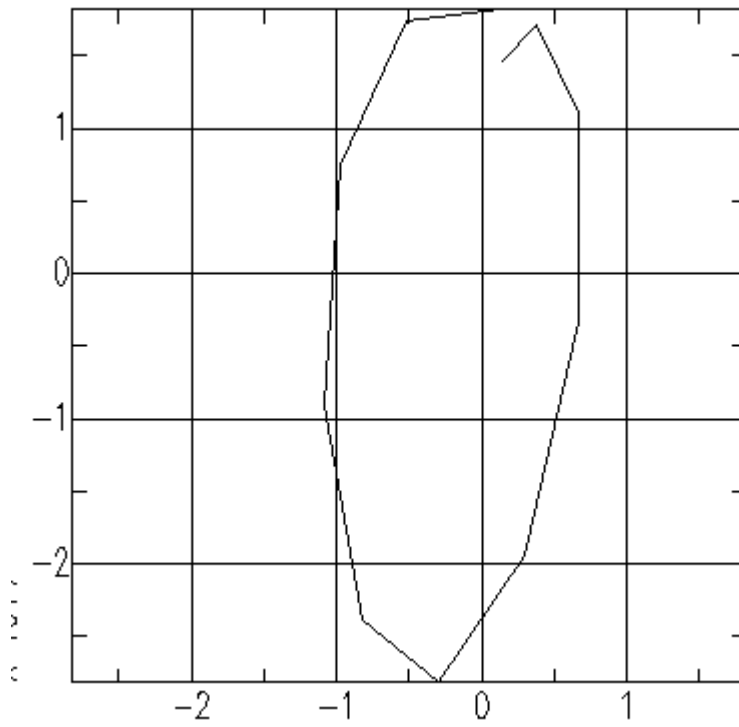


Fig.51 Particle motion (Z/R components) for signal in fig 50, considered Rayleigh wave.

We computed the FTAN analysis of the signal extracted, as shown in Fig. 52. The inferred Vs structural model (fig.53) is in very good agreement with the known lithology and with the controlled source seismic measurement (Chap.4).

Structural model in Fig. 53 was used to computed a synthetic signal. We computed Rayleigh fundamental mode for a point source with modal summation technique (Panza, 1985). Fig. 54 shows the comparison between signal recorded and synthetic one. Fig. 55 show the Particle Motion (Z/R components) for the synthetic signal. The two signal are in very good agreement and confirm we extracted Rayleigh fundamental mode.

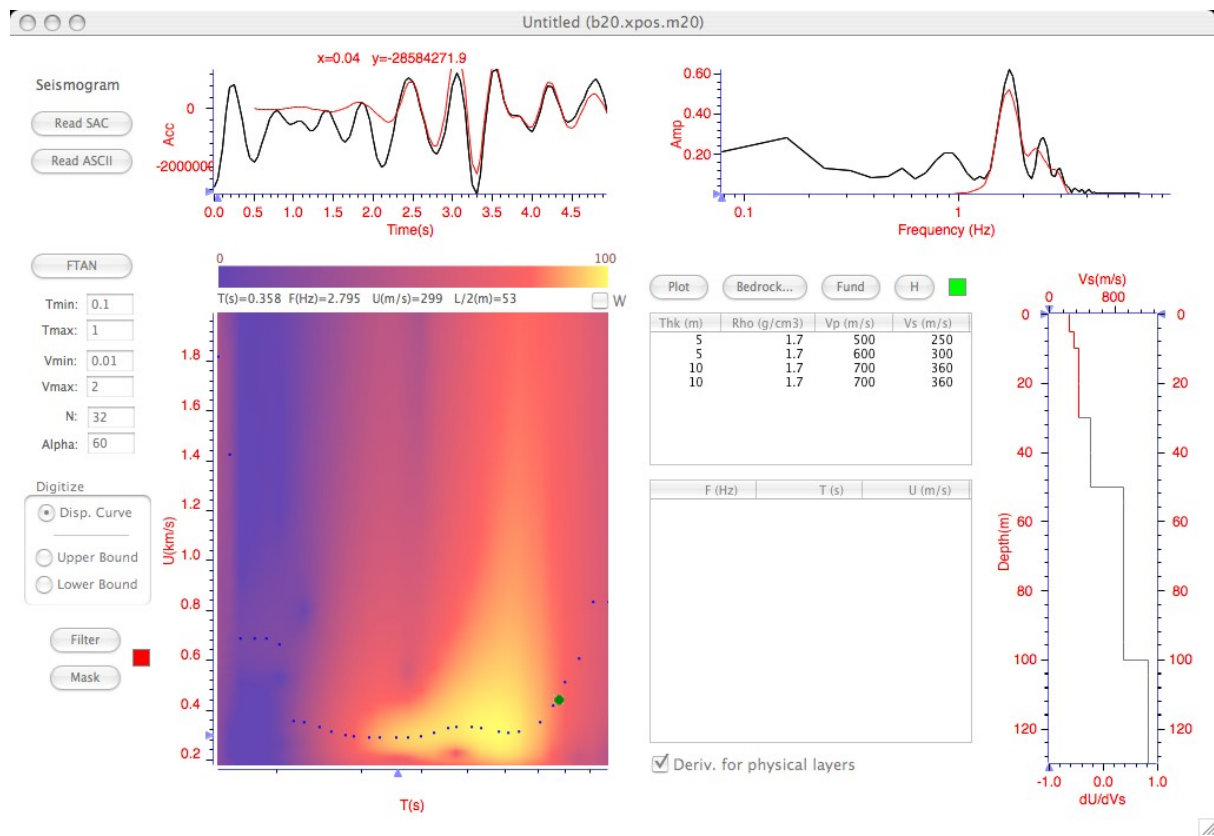


Fig.52 XFTAN Analysis of Signal in Fig. 50. In red the signal extracted considered Rayleigh fundamental mode.

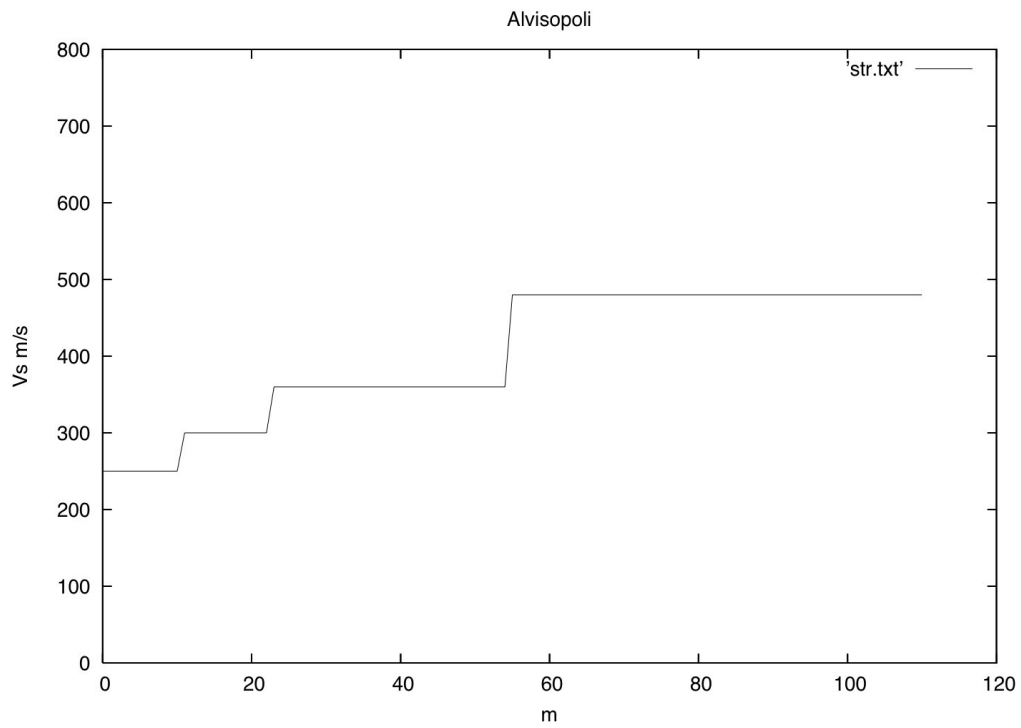


Fig.53 Vs structural model inferred for Alvisopoli

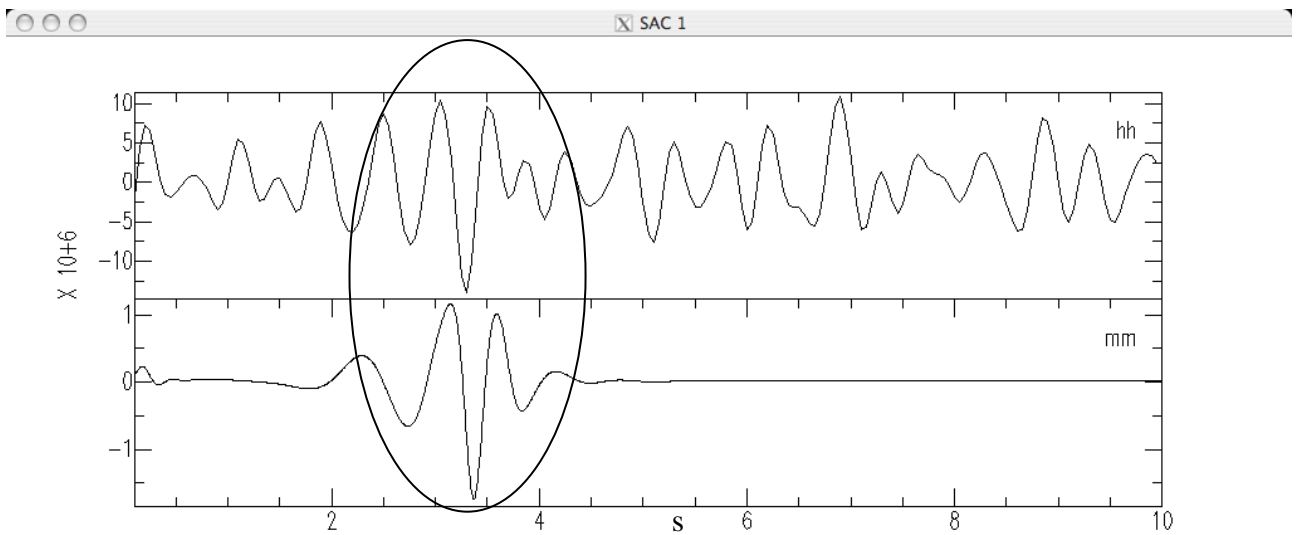


Fig 54 Signal extracted (above) and synthetic (below)

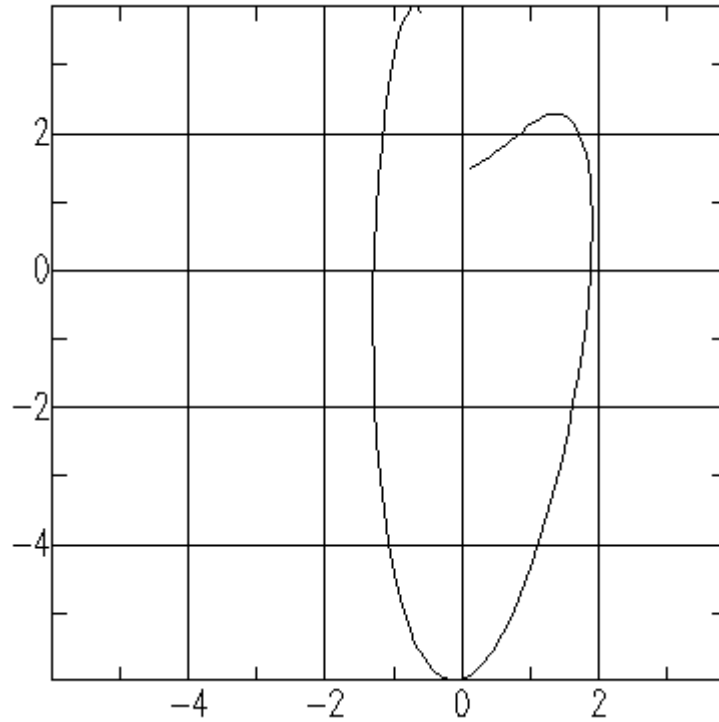


Fig.55 Particle motion of synthetic signal (Z/R components)

5.4 ESAC-NCF Comparison

To compare the result of an ESAC (Extended Spatial AutoCorrelation) array with that of NCF method, we installed 2 stations (1.7 km apart) in Asseggiano, in the Venice hinterland, acquiring seismic noise for 75 minutes. The station were 3 Components broad band receiver with 128Hz sampling. Map in Fig. 56 shows the array stations. NCF was computed between station A and H.

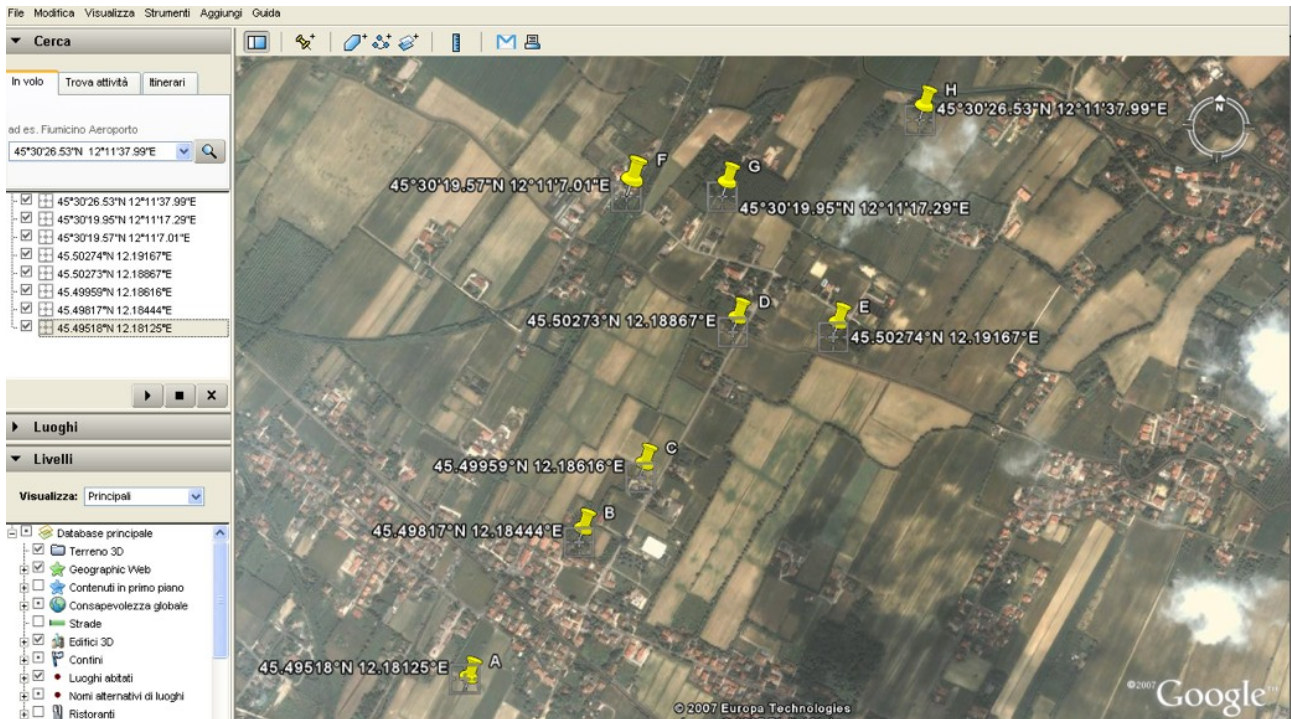


Fig.56 Asseggiano array - NCF test site

Fig. 57 shows the Noise Cross Correlation Function extracted. We performed the time cross-correlation of the signals recorded for vertical components in the frequency range 0.5- 2Hz applying butterworth filters. We computed cross correlation with several time windowing that confirmed the stability of the signal considered as the fundamental mode Rayleigh wave Green function.

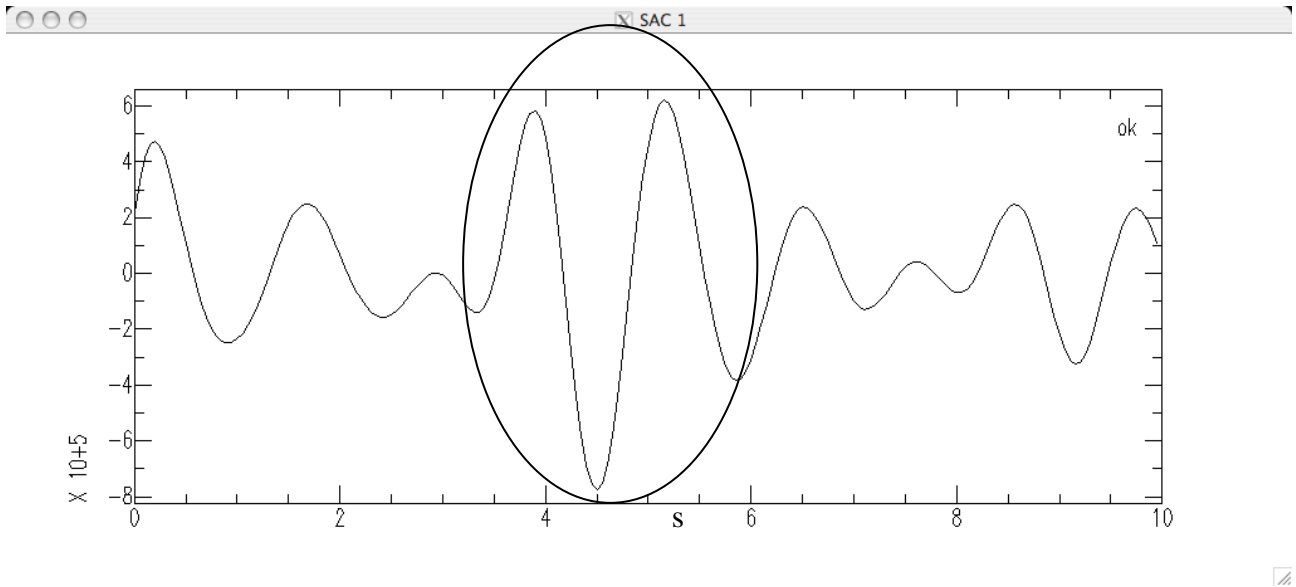


Fig 57 NCF computed in Asseggiano

We applied the Frequency-Time Analysis to the signal extracted. The FTAN map is in Fig. 58. The use of FTAN permitted to readily identify the Rayleigh fundamental mode Group velocity dispersion.

Figure 59 shows the NCF extracted and the synthetic Rayleigh fundamental mode computed for the model inferred. The Rayleigh wave group velocity dispersion curve inversion of the fundamental mode images a structure (Fig.60) in very good agreement with the ESAC one, especially for the first 50m depth.

The ESAC method is based on phase velocity, but NCF-FTAN application is preferable, cause it doesn't suffer the indetermination of the number of cycles of the phase spectrum, that is instead the Group one.

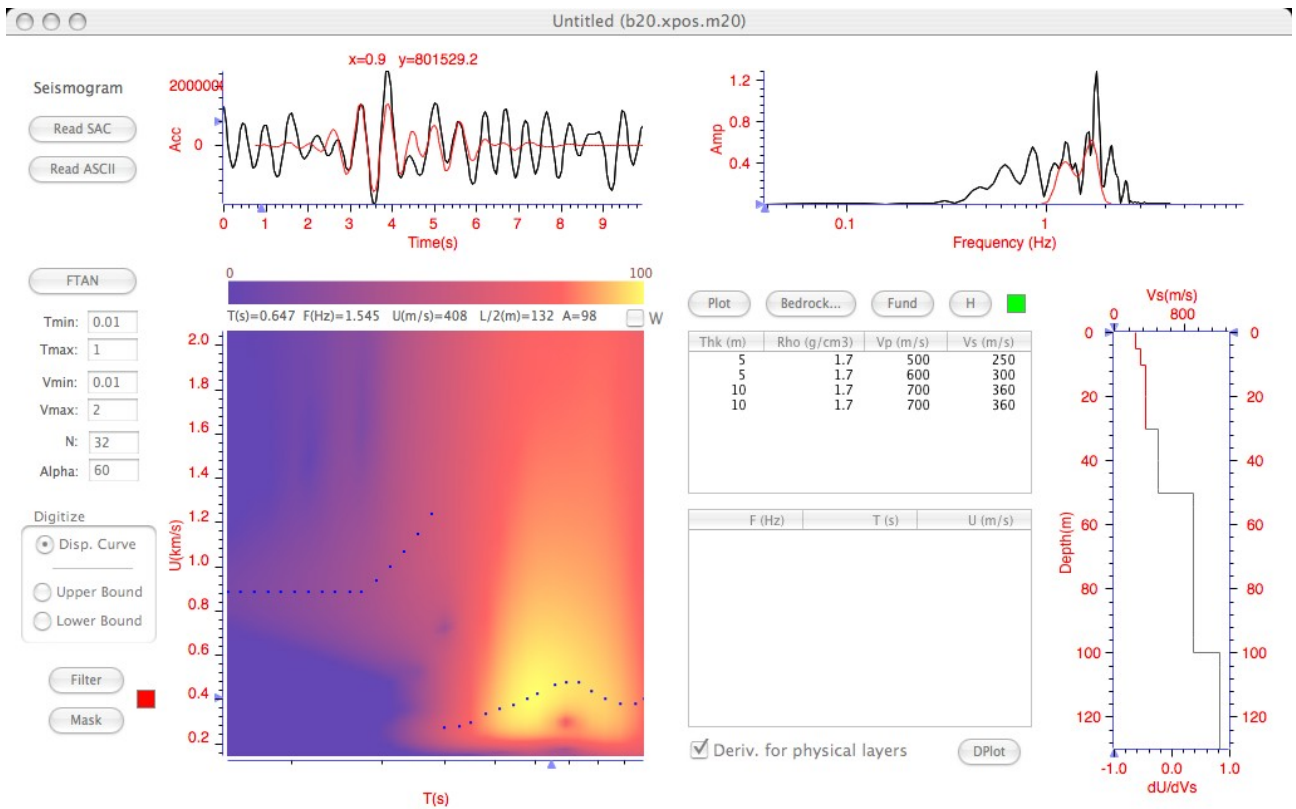


Fig.58 XFTAN Analysis of Signal in Fig. 54. In red the signal extracted considered Rayleigh fundamental mode.

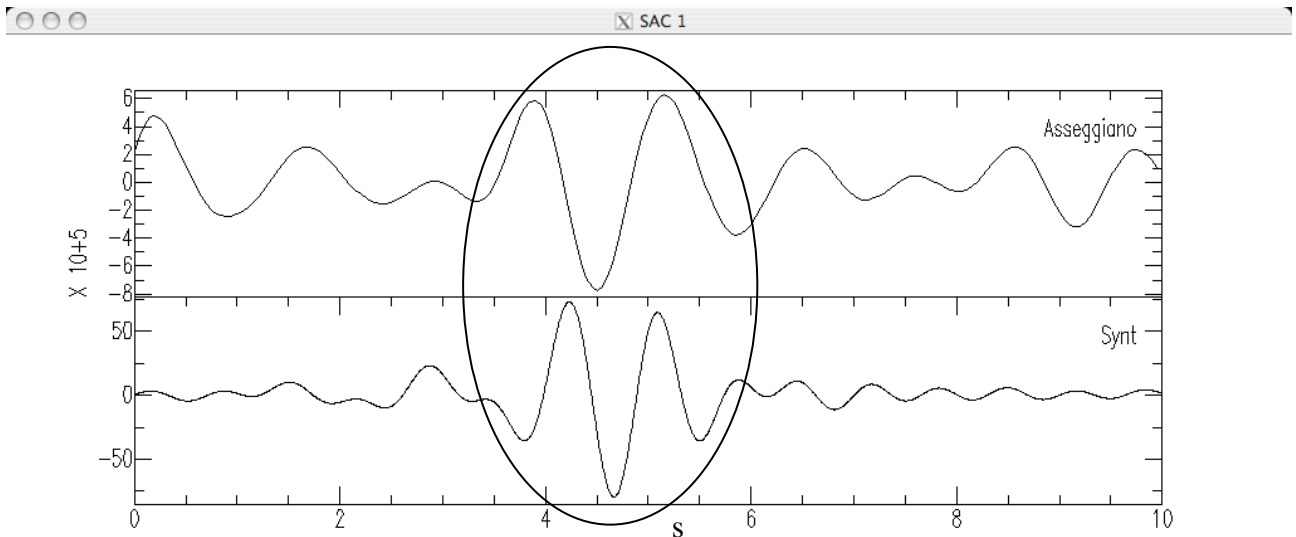


Fig.59 Signal extracted (above) and synthetic (below)

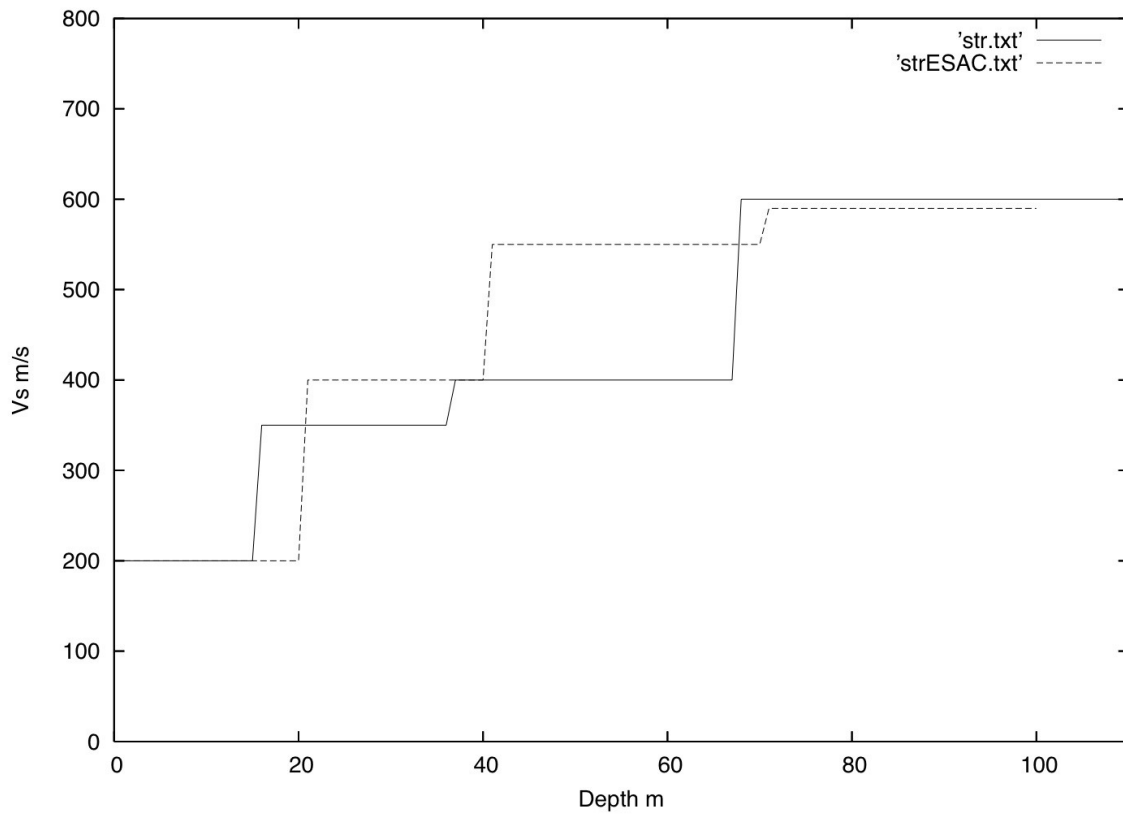


Fig.60 ESAC and NCF structural model results

The NCF-FTAN method described, being based on Group velocity measurements, is by far more accurate than any other method based on Phase velocity measurements that suffer intrinsically for the undetermined number of cycles of the phase spectrum and, when signals are contaminated by higher modes, for the difficulty of isolating the fundamental mode (Nunziata, 2005).

5.5 Long time Noise Cross Correlation

After short time NCF test, we performed a long time cross correlation of seismic noise records between the stations 'Malafesta' and 'Bibione' (see Fig. 41).

We computed the cross- correlation for days record length, with several time windowing. The data are incomplete, cause not all the 6 month record is available. Considering the aim of the study was to record seismic local events, some records not containing signals related with seismic activity were lost. Anyway more than 100 days of seismic noise with UTC synchronized timing was recorded.

Many attempts, computed for several days in the period march- september 2006, didn't give any results. It seemed that no coherent noise is observed, and no fundamental mode Rayleigh wave Green function are detected (Fig. 61).

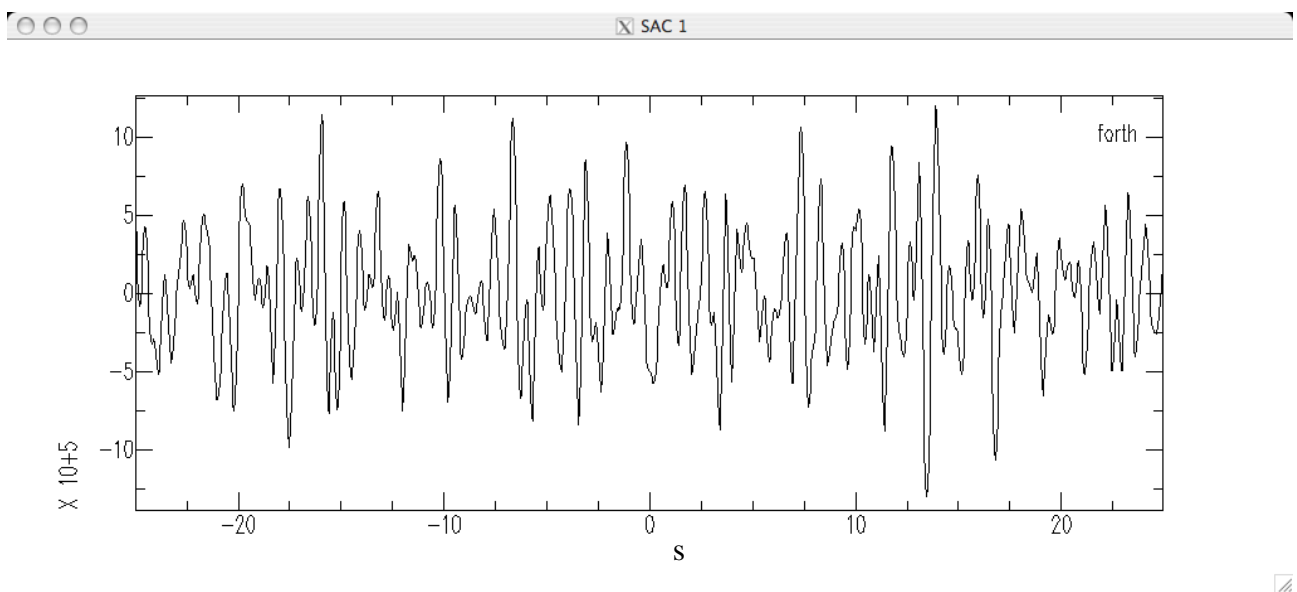


Fig 61. Example of NCF (positive and negative parts) with no evident noise coherence between Malafesta and Bibione

We considered 2 causes: first the time limitation of cross correlation timing (that appears however sufficient for 20km inter-distance), second the possible preferred noise sources. We focused our attention on the second aspect, cause also extending the data time, no coherent noise was detected.

The principle noise sources identified in the studied area are: sea, river and highway. The Highway is near Malafesta Station, but is only a 4 lanes highway. We do not believe that single traffic source can control our noise field for 22 km.

Considering station aligned perpendicular to the coastline, we identified sea and river are the strongest noise sources. Probably the absence of results obtained are due to the river-sea noise interaction. The river is close to the 2 stations and parallel to our station alignment. It is a constant source, along all his path, and does not permit the unphasing of noise signal. The sea activity is obviously important, in fact, computing NCF during during sea storm the sea noise is dominant.

5.5.1 Sea noise and diffuse noise

Thanks to Dr. G. Cavaleri, of the Venice oceanographic department of Italian National Research Council, we obtained the sea wave amplitude of Gulf of Venice for the period of seismic recording. Than we focused our cross correlation of ambient noise for the days with strongest sea storm, when the sea noise source is clearly dominant.

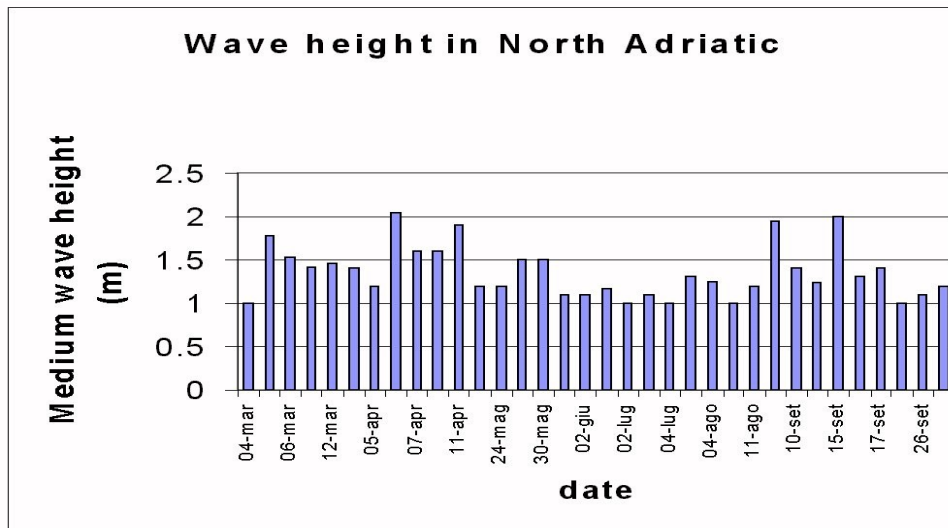


Fig. 62 Wave height in Adriatic sea (from CNR) in the recording noise period.

Only few days the medium highness of sea wave reached 2 m, around April 6 and 15 September. 15 September recording lacks, so we focused on the April days. These are the only noise cross correlation attempt that detected a coherent noise that propagate from coastline to inner land. The directional analysis of seismic noise, clearly shows the sea source direction (45° from Instrument orientation in Fig.63).

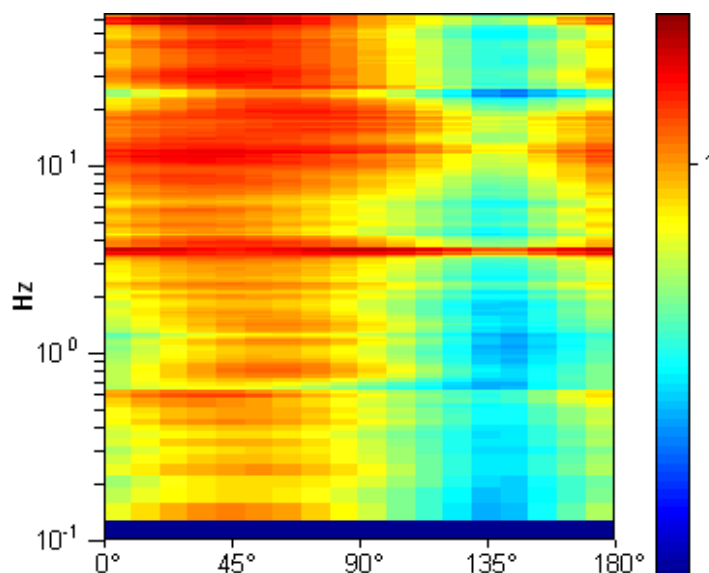


Fig.63 Directional Analysis of seismic noise for 6 April, denote 45° orientation source.

We computed cross correlation for the sea storm period (almost 18 h), with several time windows, that confirm that the signal extracted is evident only in one side of Noise Cross Correlation Function. This means noise travel only from 'Bibione' station to 'Malafesta' station, coming from the sea. The signal is however very noisy (Fig. 64).

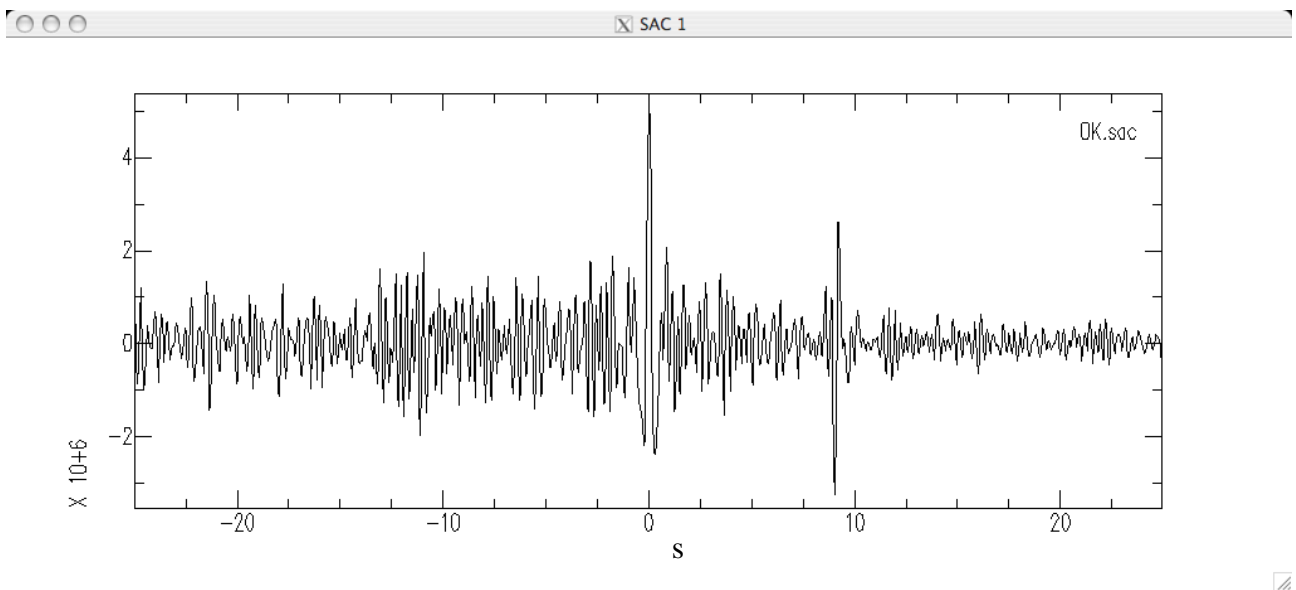


Fig. 64 NCF of 6- 7 April Period, Bibione as master. Denote the 10s signal only in the positive part and the bad starting point at 0.

Figure 65 shows the same signal filtered in the 0.1- 1.5 Hz pass band, only the positive NCF part, taking Bibione as master. The signal is hardly considerable media Green Function, cause the starting point is distant from 0.

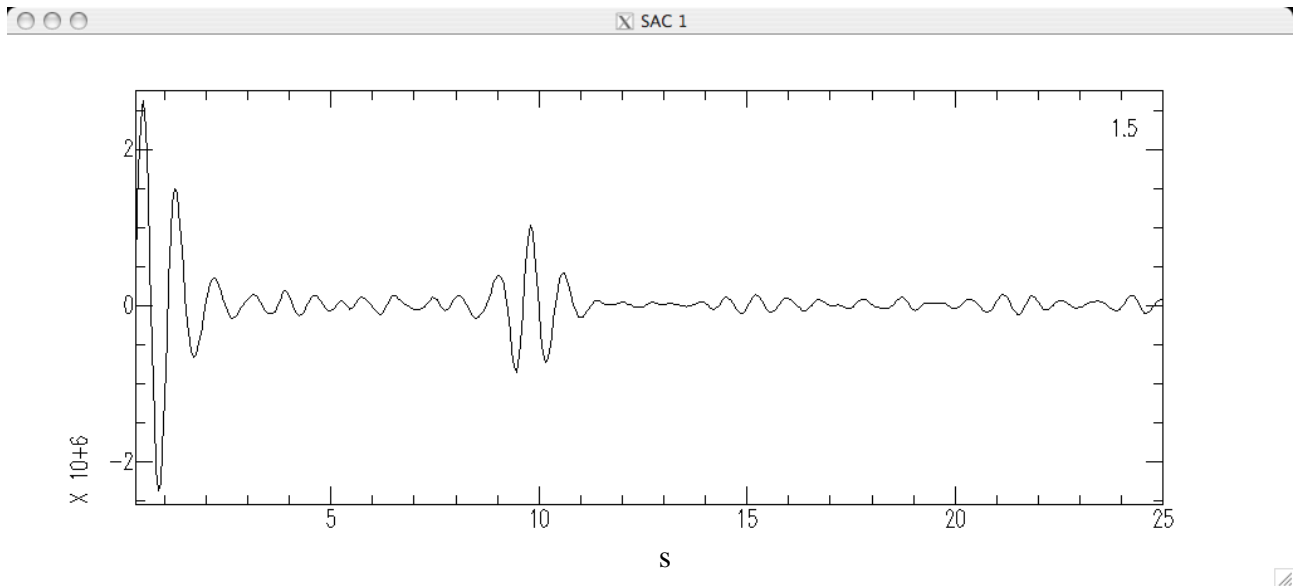


Fig. 65 Positive part of NCF of the same signal of Fig.60, filtered in 0.1- 1.5 Hz pass band. Denote the bad starting signal.

We do not consider the signal computed to be the Green function of the media. First of all the strong signal at the beginning of the series is clearly not related to the Green Function. The signal evident at 10s is very difficult to construe, and it seems too fast to be related to Rayleigh velocity. Wave incident are probably not perpendicular to our array, so stations inter- distance geometry could not be the assumed. On the other hand we identify the signal only in the positive part of cross correlation and, looking for noise diffuse propagation in large inter- distance record, this confutes noise theory.

We tried to focus on 3 days in September, with normal sea wave activity. We separated the record in 8 h windows. Then we performed a cross correlation on each window and stuck all the window results together. Figure 66 shows the resulting NCF for the positive part, taking Bibione as master filtered in the 0.1- 1.5 Hz. Figure 67 shows the result NCF for the negative part, taking Bibione as master, filtered in the 0.1- 1.5 Hz.

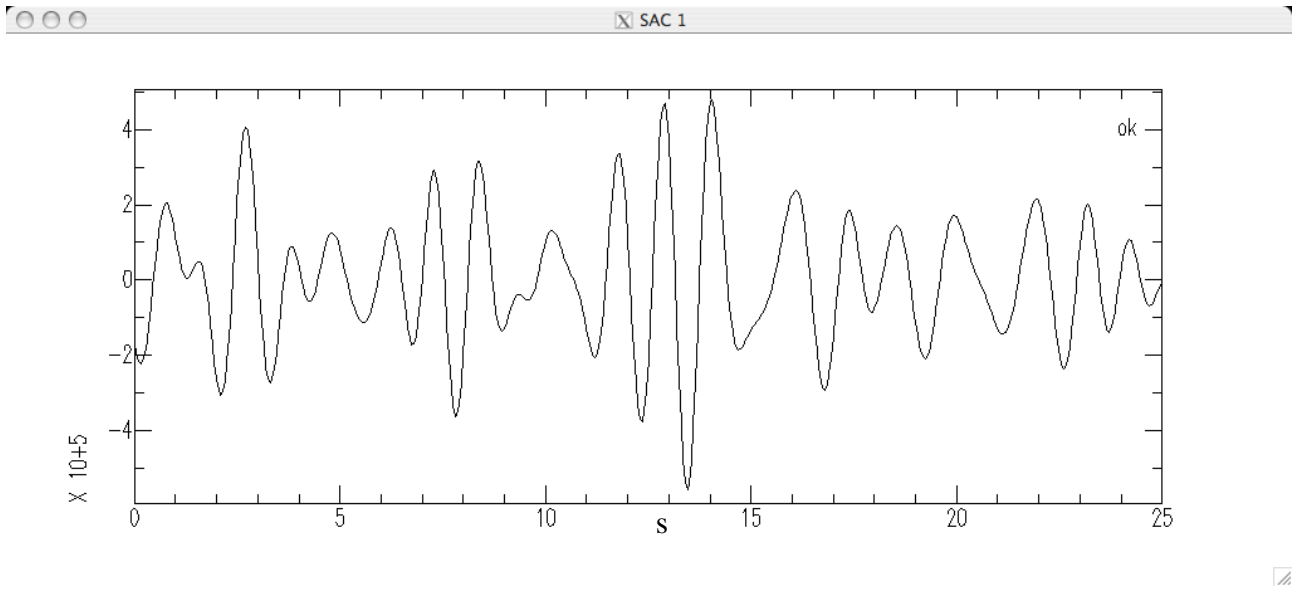


Fig.66 NCF of 9- 11 September period, Positive part and Bibione as Master. Filtered in the 0.1- 1.5Hz pass band.

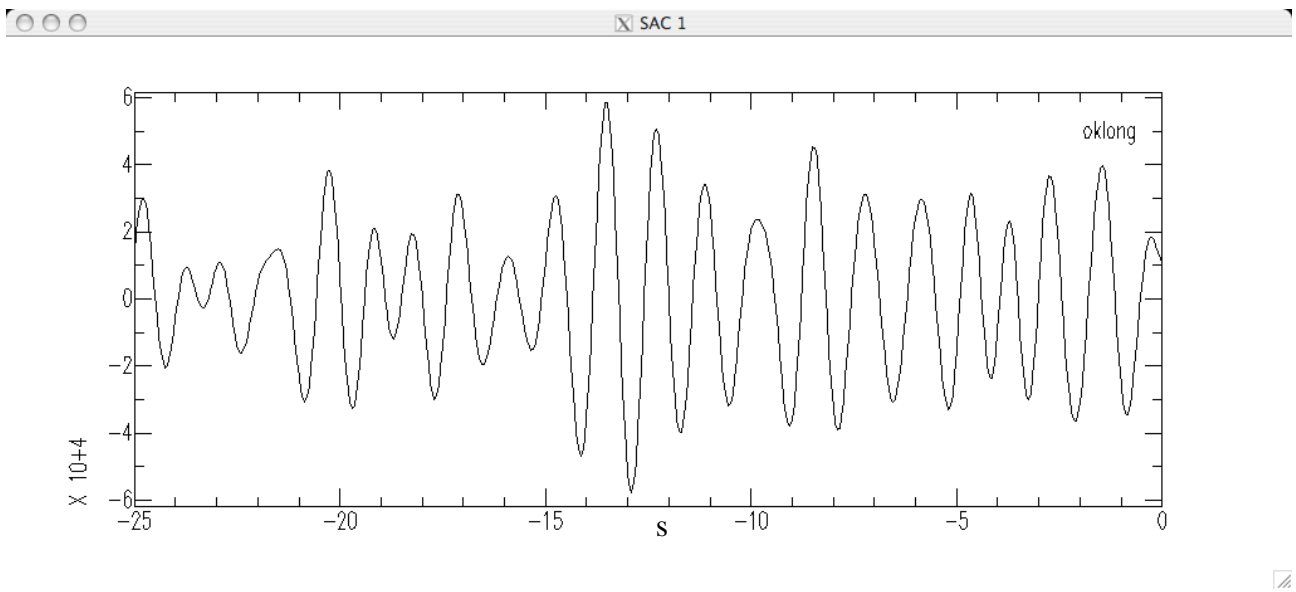


Fig.67 NCF of 9- 11 September period, negative (Note X axes orientation) part and Bibione as Master. Filtered in the 0.1- 1.5Hz pass band .

As evident a signal at 13s is recognized. The important aspect is that the same signal is found for both parts of the cross correlation, positive and negative (Fig 68). This implied that we analysed a diffuse noise field that travel from station Malafesta to Bibione and vice-versa.

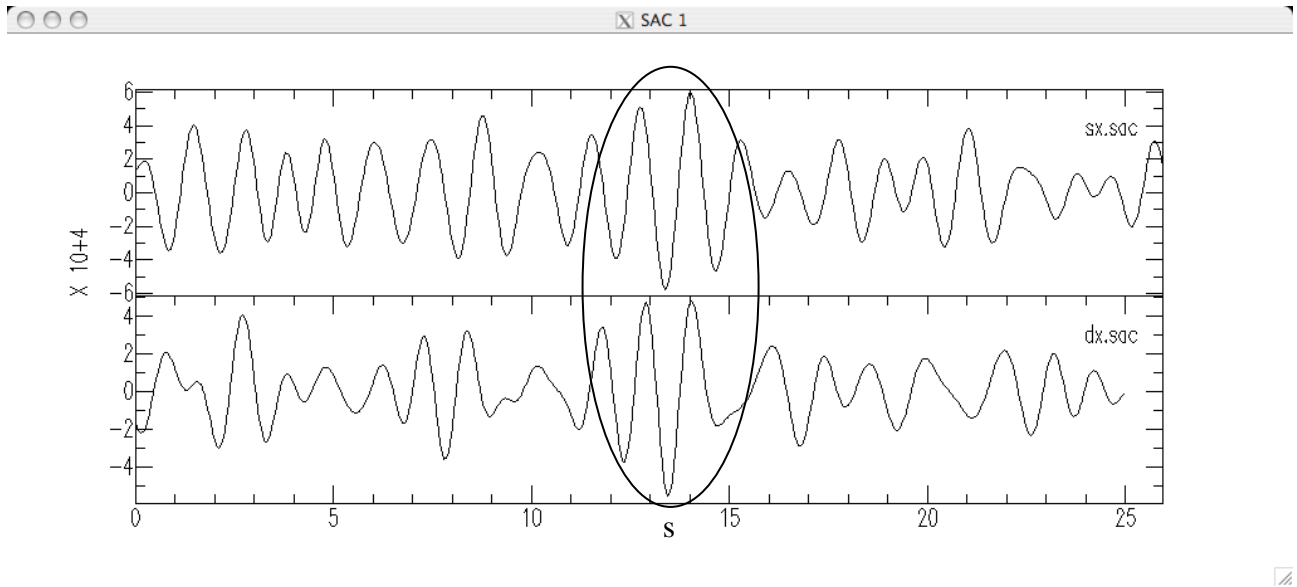


Fig 68 NCF of 9- 11 September period, filtered in the 0.1- 1.5Hz pass band. Negative and positive parts. Denote 13s signal.

A Frequency Time analysis of signal was done (fig.69), the Vs model inferred by trial and error method is in Fig.70. In Figure 71 we compared the signal extracted with the synthetical one for the inferred structure. The synthetical signal was computed for fundamental Rayleigh mode with a point- source, like the precedent cases.

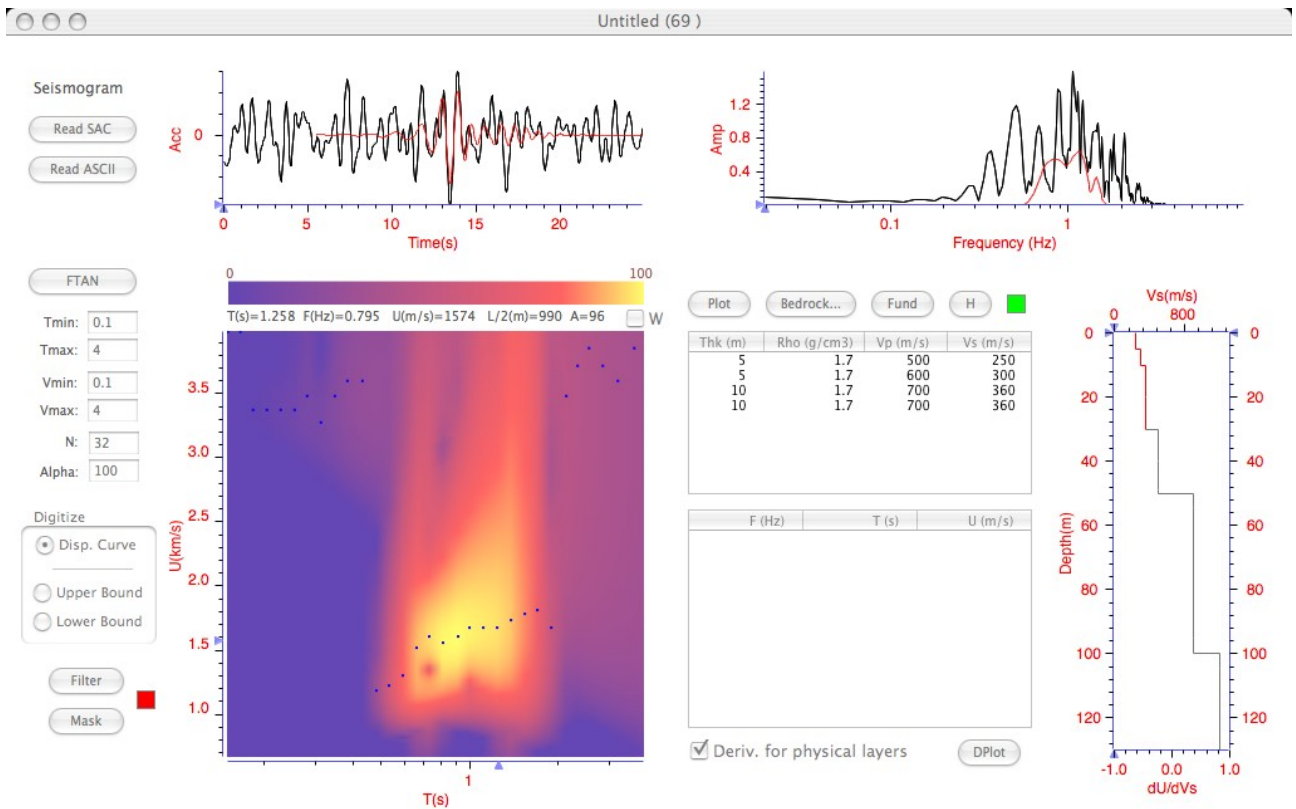


Fig. 69 FTAN Analysis of Signal in Fig 66. In red the signal extracted considered Rayleigh fundamental mode.

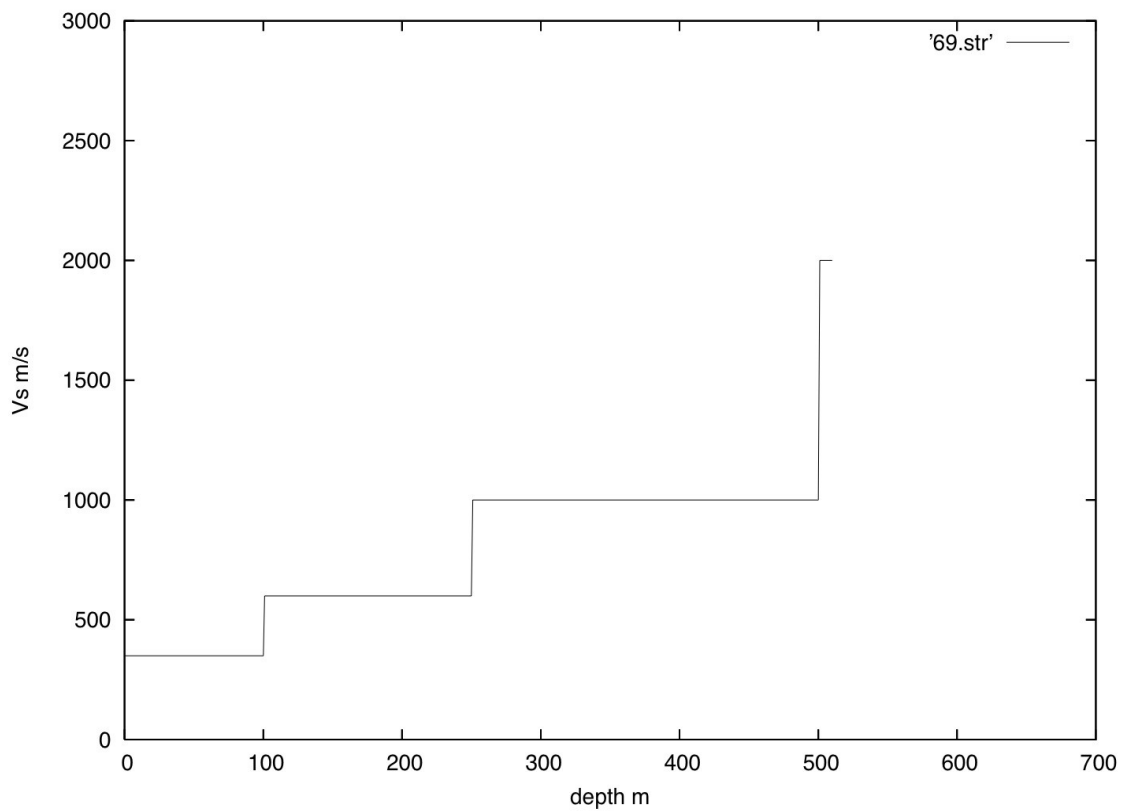


Fig. 70 Inferred structure for signal in fig. 62 with FTAN analysis.

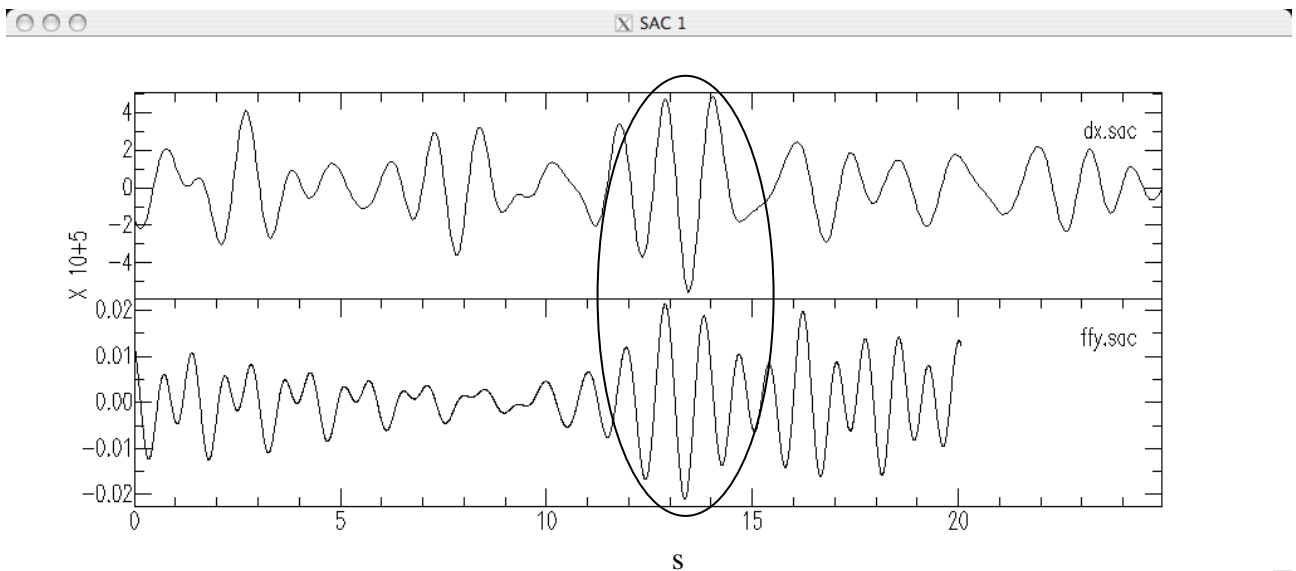


Fig.71 NCF Extracted signal (above) and synthetic signal computed for structure of fig.65 (below). Denote 13s signal.

The Rayleigh fundamental mode dispersion curve indicates a vary fast velocity for the bedrock basement: 2100m/s at 500 m depth. This value is in good agreement with the Agip one (chap.2), that indicate a V_p of 4000 m/s for the 'cavanella formation'. It is also in good agreement with the Earthquakes Ftan analysis explained in chapter 3. The frequency of the signal extracted is linked to a rather low frequency and doesn't provide much information about the upper subsoil. For this purpose we performed the same analysis with 2 mobile station with shorter inter- distance (chap. 5.3).

5.6 Discussion

We computed time cross correlation of seismic noise between 2 mobile stations in several conditions. Many records were useless, cause no coherent noise appear in the NCF (noise cross correlation function). We had good results in 3 cases. For short station inter- distance, in presence of directional seismic noise source and for long station inter- distance in case of (rare) diffuse noise field. For our long period recordings only few days gave us the attended results. If we believe that 6 month of record work risk to be complete unsuccessful, we can consider it a not repeatable experience. But for short inter distance condition, in presence of noise sources, we evaluated Shear wave till a depth of 150m with very cheap and easy experiments. We consider this a great improvement for seismic scenario study, where no shear wave model is known. For long period recording we think that only existing networks are useful. Networks, permanent or mobile, installed for Earthquake recordings or Volcanoes monitoring, could be successfully used for these purposes. If continuous recordings stop to be useless 'noise' and become useful signals, a new topic for earth interior study could be developed. Signal computed is often hard to construe, but computation of particle motion and, above all, correlations with known subsoil velocities, can be helpful. In conclusion, considering that even in developed country shear velocities of soil are often unknown, this methodologies could be a modern answer, preferable to many literature uncertain data.

Chap.6

Structural models and Deterministic Scenario

6.1 Structural Models

The results of the experimental work, explained in chapters 3 and 4 , are 3 main subsoil structural models of the area in exam. The defined models are specific of the northern part, the central part, and the southern part. The results compare well with other authors' experiences, previous works and geological knowledges.

Fig. 72 shows the resulting structures. It is evident that structures have different characteristics for the upper subsoils and for the bedrock depth, but they have the same Vs structure for the common part. In fact the upper subsoil was defined mainly by controlled source seismic prospecting, and the bedrock depth was assumed by single station noise measurements.

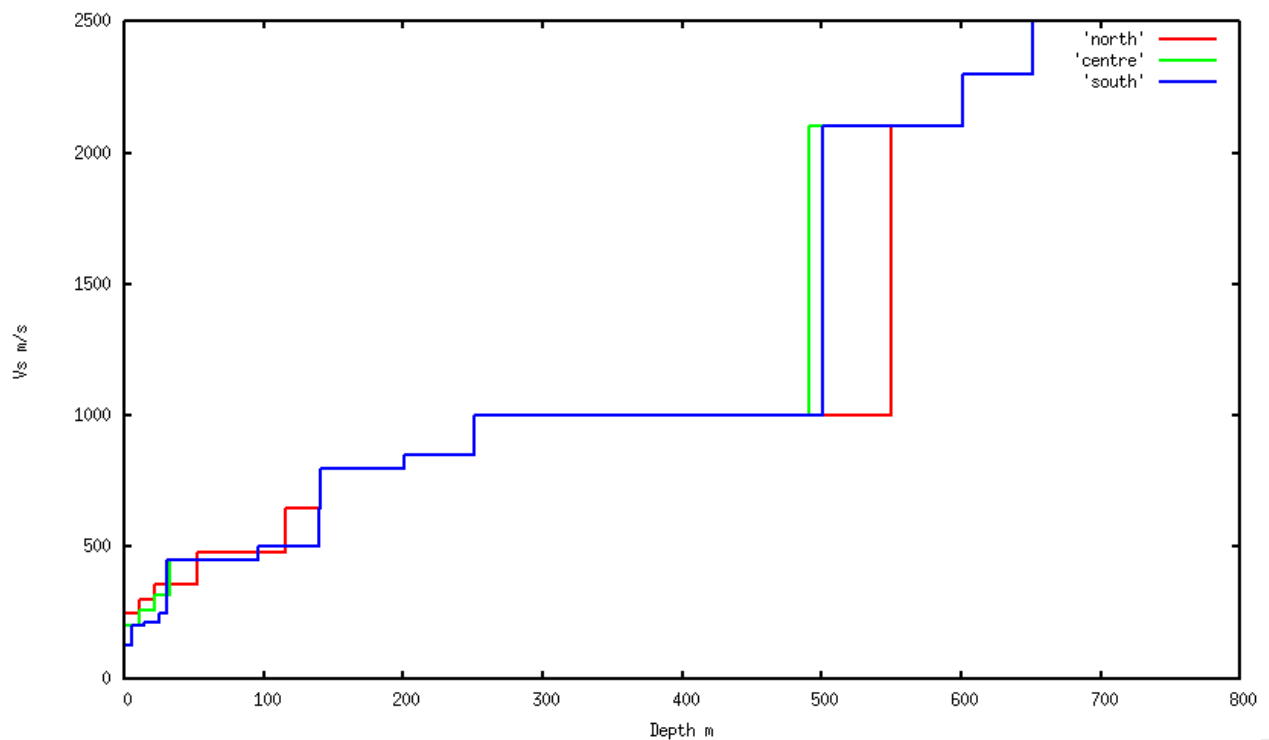


Fig. 72 Structural models inferred.

Depth structure between 150 and 500 m was inferred only by long time cross

correlation of the Malafesta- Bibione stations, and is obviously referred to a 1d model of all the studied area.

The FTAN methodology, applied to impulsive active energy, permitted to define the V_s structure of the first 30-60m. Noise cross correlation of local anthropic source is able to reach 150m of deep investigation. HVSR method gave us only a qualitative information on the bedrock rising in Cesarolo zone, confirmed by well investigation (480 m). Only a long noise cross correlation processing was able to reach the deeper subsoil between 150 and 500m, and gave us a 1d model of all the area in exam.

Fig 73 shows a comparison between the structural model inferred and the results of a deep seismic reflection prospecting near the studied area. The study was conducted by Della Vedova et al. (1999), mainly for hydrological purposes. As it can be seen, the bedrock depth (Pliocene roof) is consistent with our result. The main important aspect is that the 2 obtained inhomogeneities of V_s structure at 130m and 280m, are consistent with 2 levels founded by Della Vedova et al. The 280 m level are related to a thick gravel level confirmed by several wells. The upper level is a clear seismic reflection related to stiff clay level. The levels depth are quite deeper in our zone, that is quite southward the Della Vedova studied zone. This is in agreement with the lithology sedimentation trend.

In conclusion we estimated V_s till 500m depth, as was our study aim. These results lead to the possibility of a realistic ground motion scenario, and meet the deterministic approach need of realistic modelling.

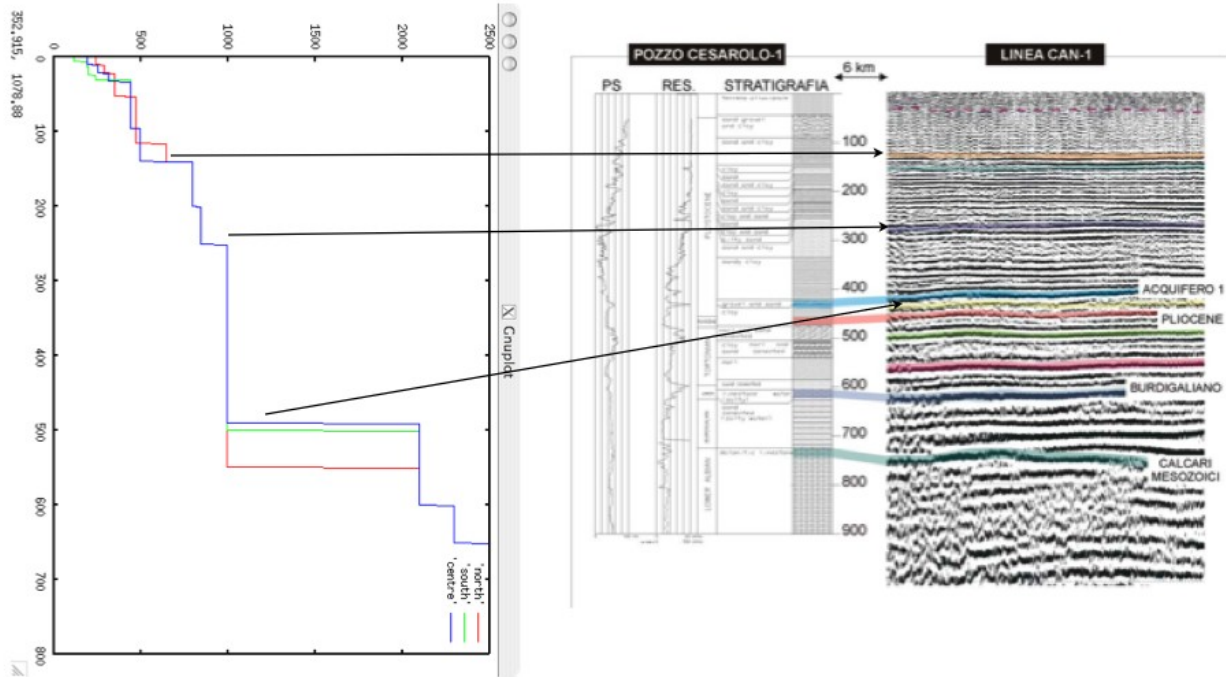


Fig.73 Reflection Seismic section and wells logs (right) near the studied area compared with our results (left). Denote the strong reflector at ca 150 and 280m and the bedrock at 500m.

6.2 A Brief Introduction to Seismic Hazard and Deterministic Approach

Here we report a brief introduction to deterministic Hazard Scenario methodologies. This is not the specific Thesis aim and we remand to References for details (e.g. Panza G.F. 1985, Panza et al. 1987, 1993, 1997, 1999, 2001).

The mapping of the seismic ground motion, due to the earthquakes originating in a given seismogenic zone, can be made by measuring seismic signals with a dense set of recording instruments when a strong earthquake occurs. With the deterministic approach we can do it by computing theoretical signals, using the available information about tectonic and geological/geotechnical properties of the medium, where seismic waves propagate. Strong earthquakes are very rare phenomena and it is therefore very difficult (practically impossible in the near future) to prepare a sufficiently large database of recorded strong motion signals that could be analyzed in order to define generally valid ground parameters, to be

used in seismic hazard estimations. While waiting for the enlargement of the strong motion data set, we consider the only useful approach to perform immediate microzonation is the development and use of modeling tools based, on one hand, on the theoretical knowledge of the physics of the seismic source and of wave propagation and, on the other hand, exploiting the rich database about the geotechnical, geological, tectonic, seismotectonic, historical information already available (e.g. see Field, 2000, Panza et al., 2000).

This work is by its nature multidisciplinary since information are requested from different disciplines, as seismology, history, archaeology, geology and geophysics in order to give to the engineers reliable building codes. The realistic modelling of ground motion requires, in fact, the simultaneous knowledge of the geotechnical, lithological, geophysical parameters and topography of the medium. The thesis aim is in fact the use of modern applied geophysics in order to parametrize shear waves profiles, that represent often the most important and absent parameter.

Seismic hazard problem is the determination of effects associated to earthquakes. The input for seismic risk analysis can be expressed with a description of the ground shaking intensity due to an earthquake of given magnitude (ground-shaking scenario), or with probabilistic maps of relevant ground motion parameters. An often used parameter in seismic hazard is the Peak Ground Acceleration, that is a single value indicator relatively easy to determine but that leads to incorrect risk estimates. It can not describe the effect associated to ground shaking since the frequency content and the duration of a seismic wave-train can play a decisive role. It is recognized in fact that the characteristics of ground motion such intensity, duration and frequency content are relevant to estimate its potential damage.

In a given site, a definition of seismic input can be done with 2 approaches knowing the magnitude and epicentral distance of an earthquake. The first is based on the analysis of the available strong motion databases, collected by dense seismic networks. The second approach is based in modelling techniques, developed from the knowledge of the seismic source process and of the propagation of seismic wave, which can realistic simulate the ground motion associated to a given earthquake. This could be called a neodeterministic approach.

The ideal procedure is to follow both deterministic and instrumental approaches, in order to verify the theoretical results. But dense seismic network and rich strong motion databases are present only in North America and Japan, cause the networks installation and maintenance are very expensive. In practice, for most of the European seismic zone strong motion data are scarce, especially for our studied area, where only historical strong earthquakes occurred. In these cases only synthetic signals could be really useful for engineering needs, starting from the characterisation of the source, the path and the local geological and geotechnical conditions. This approach is however useful even when strong motion instrumental data are available, cause seismic effects are strongly source dependent, and only a realistic modelling of all the potential sources could be considered a complete scenario (Romanelli & Vaccari 1999).

The probabilistic approach can not satisfy the modern description concept of seismic effects. The principal cause is that one can not take in serious consideration the local geological aspects. It is well known local amplification is related to soft surface layers that trap seismic energy because of the impedance contrast between the soft surface layer and the underlying bedrock. Moreover, complex resonance patterns are strongly dependent on the characteristics of site topography and of the subsoil geometry. The most traditional empirical techniques for the estimation of site effects are based on the spectral ratio between signals at a sedimentary site and a reference one. Often there are no reference sites near studied area, so source influences and directional effects could not be considered. More complex aspects and limitations play an important role when only H/V noise measurements are developed. That implies, in fact, that the vertical component is not perturbed by surface layer, and can be used to remove source effects from the horizontal one.

Deterministic scenario modelling, for our studied area, remains the unique modern approach able to describe ground motion scenario of the strongest historical earthquakes occurred. With the probabilistic approach is hard to consider the specific media wave propagation, and often the seismic scenario consider only bedrock condition (e.g Italian Seismic Law 2003). The deterministic approach is, instead, useful for realistic soil-dependent ground motion scenario. We can simulate the ground motion for whatever earthquakes and for every soil condition. With the knowledge of past seismic events and the characterization of geological

condition, we can 'record' the strong motion even for historical earthquake everywhere we want. The possibility to compute realistic synthetic seismogram of strong event plays an important role in seismic engineering, and can be useful to building design.

The topic is we can reduce damage by highly detailed specific prediction of seismic ground motion. With the knowledge of accurate structures and probable, complex source mechanisms, the detailed ground motion at any site, or all sites of interest, can be determined. Using a Deterministic Approach to map seismic ground motion, we do not have to wait for earthquakes to occur, and then to measure ground motion with an extremely dense set of recording instruments; instead, with the knowledge above, we can compute these seismograms from theoretical considerations. Thus, a complete database for all sites and predicted focal mechanisms can be constructed immediately; no delay is necessary while we wait for experimental evidence and recordings.

6.2.1 Technique

This innovative modelling is based on modal summation technique (Knopoff 1964; Schwab & Knopoff 1970, Panza 1985, Florsch et al. 1991). This method applies principles of physics about wave generation and propagation in complex media, takes into account source, propagation and local site effects. Therefore it is not necessary to resort to convolutive approaches, that have been proven to be quite unreliable, mainly when dealing with complex geological structures. These techniques supply reliable information about the site response to non-interfering seismic phases, but they are not adequate in most of the real cases when the seismic sequel is formed by several interfering waves (Panza et al., 2000, Panza et al. 2001).

Modal summation technique for synthesizing realistic seismograms has its roots in the middle of the 20th century when Thompson (1950) and Haskell (1953) proposed a matrix method to efficiently compute the dispersion of surface waves in multilayered media. The method has been modified by many researchers during the second half of the century (e.g. Schwab and Knopoff,

1972; Florsch et al., 1991). The main problem in practice was the loss of precision when dealing with higher modes at high frequencies, which was solved by Schwab (1970) and Schwab et al. (1984). Introducing the seismic source via the formalism proposed by Ben-Menahem and Harkrider (1964), Panza (1985) gave an example of Rayleigh wave computation for frequencies up to 1 Hz for continental and oceanic models consisting of 70 layers and extending to depths of 1100 km. The efficient Rayleigh wave computation for frequencies up to 10 Hz has been carried out by Panza and Suhadolc (1987).

Florsch et al. (1991) gave the solution for Love and SH-waves. Although the modal summation offers an efficient way to obtain realistic estimates of ground motion, the assumption of horizontal isotropic layering is often inadequate. This is true in cases when the parameters used to define the properties of the media through which the seismic waves propagate vary rapidly at horizontal distances comparable to the wavelengths in question (laterally heterogeneous media). Our studied area, cause its geological homogeneity, could be considered an ideal 1d modelling condition, and no 2d hybrid techniques are applied.

Synthetic seismograms of the vertical (VER), transversal (TRA) and radial (RAD) components of ground motion are computed at a predefined set of points at the surface. The scaling of the signal's spectra to the assumed seismic moment use the curves proposed by Gusev (1983) as reported in Aki (1987).

6.3 Scenario

Two earthquakes are selected to compute the seismic scenario of our area in exam. The most dangerous known historical seismogenic zone, for the studied site, is the Cansiglio/Polcenigo area. The main earthquakes occurred in 1873 (Belluno) and 1936 (Cansiglio). The location of the former is uncertain, and his magnitude is fixed in 6.4. The latter is well studied and defined, and has magnitude 5.8. We prefer to analyse the less known strong earthquake known as the Montello earthquake then the Cansiglio one. Montello Earthquake is an hypothetical earthquake, with no certain historical data, and is common opinion it could be

associated to a 6.7 magnitude event, the strongest one.

We simulate to record the events with 24 stations, one station every 1 km for the entire area in exam. This application well explains the power of the modal summation technique to simulate realistic ground motion. The plane parallel geological condition and homogeneity of the studied zone suggests the 1D approach, cause no 2d influence are attended.

We computed, for all the 3 components, a seismogram for each virtual station for displacement, velocity and acceleration.

We must underlain that, due to the uncertain data of historical events, every result must be used with care. The Macro-seismic Intensity is obviously hard to define and or historical earthquakes suffers of data collection lack. The relation between MCS and Magnitude by Panza et al. (1997) is shown in table 6.

I mcs	PGD (cm)	PGV (cm/s)	DGA (g)
V	0.1- 0.5	0.5- 1	0.005- 0.01
VI	0.5- 1.0	1.0- 2.0	0.01- 0.02
VII	1.0- 2.0	2.0- 4.0	0.02- 0.04
VIII	2.0- 3.5	4.0- 8.0	0.04- 0.08
IX	3.5- 7.0	8.0- 15.0	0.08- 0.15
X	7.0- 15.0	15.0- 30.0	0.15- 0.3
XI	15.0- 30.0	30.0- 60.0	0.30- 0.60

TAB. 6 Macroseismic Intensities conversions from Panza G.F , Cazzaro R. e Vaccari F. (1997) correlation between macroseismic Intensities and seismic ground motion parameters

Tab. 6 explains that, roughly speaking, one grade of Imcs correspond to a doubling of peak motion value. This implies that, basing our knowledge on obviously uncertain historical earthquakes, we can not reach a precise description on attended acceleration. Most of hazard maps produced for territorial planning have only 'presumed' precision, with no theoretical explanations. It is author's

opinion that hazard Maps with 0.025g step follow more the government needs than the scientific one.

6.3.1 Historical Earthquakes

The 5.8 (?) Cansiglio Earthquake, 10 October 1936, is a well studied event. In this Thesis we did not focus on the characterisation of the event, and we rather used literature data. We based on the recent Pettenati, Gentile and Sirovich work (2005), that inverts macroseismic data for the 1936 Cansiglio event.

The Table below explain the model inferred by Pettenati et al.

CANSIGLIO EARTHQUAKE 1936

Parameters	Model
Latitude	46.10 N
Long.	12.48 S
Depth	15.3 Km
Length	16.7 Kmlong strike, 2.9 Km antistrike
Strike	238°
Dip	47°
Rake	88°

The Belluno Earthquake, quite the north of the Cansiglio one, occurred in 1873. It is associated to a 6.4 magnitude event. We used another macroseismic inversion study from Pettenati and Sirovich (2002).

BELLUNO EARTHQUAKE 1873

Parameters	Model
Latitude	46.18 N
Long	12.40 E
Depth	12 Km
Strike	217°
Dip	52°
Rake	53°

The Montello earthquake is probably the strongest hypothetical earthquake that involve the Veneto pre- alp region. There are many uncertain data on its position and effects. It is associated to a 6.7 magnitude (Well and Coppersmith 1994), and its definition is inferred by the seismogenetic considerations of the area. As the table below explains, the source parameters are assumed close to the nearby Cansiglio event. We used the event definition from Priolo et al. (2004) and Valensise et al. (DISS 3.0.1).

MONTELLO EARTHQUAKE

Parameters	Model
Latitude	45.8 N
Long.	12.05 – 12.12 E
Depth	7 Km
Strike	240°
Dip	40°
Rake	80°

Our aim was to generate the worst seismic hazard scenario for the studied site. We considered the 2 most dangerous events occurred; the Belluno earthquake and the Montello one.

We identified 20 virtual receivers from station 1 (North) to station 20 (South),

as it could be seen in the Figure 74.

We divided the studied area in 3 parts: north, central and south, with the 3 structural models identified (see chap 6.1). For each part the displacement, velocity and acceleration for vertical, radial and transversal components were computed. His amounts to more than 100 synthetic seismograms. In every seismograms set, the maximum value reached is shown.

The sets of time histories for the 2 scenarios are shown in [Appendix 1](#). The results obtained are directly useful for engineering needs, and show one powerful application of the deterministic approach, that is the ability to compute realistic ground motion scenarios for historical earthquakes.



Fig. 74 Virtual receivers on the studied area

The computation of realistic synthetic seismograms, taking into account source, propagation and site effects gives a powerful scientific tool for microzonation. The procedure is scientifically and economically valid, cause there is no need to wait for strong earthquake occurrence.

The difficulties connected with a correct site effects estimation are the separation of the factors contributing to the seismic signal: source effect, path effect, and site effect. A modern deterministic approach seems to be the possible solution to this difficult task. The results could be used by civil engineers in the design of new seismo-resistant constructions, and for prevention aspects of Civil Defence.

Chap. 7

Conclusions

This Thesis mainly concerns two topics of modern applied geophysics: surface wave dispersion and seismic noise.

Surface wave dispersion study is performed with the Frequency Time Analysis (FTAN, Levshin et al 1972,1992). The method applied, being based on Group velocity measurements, is by far more accurate than any other method based on Phase velocity measurements, that suffer intrinsically for the undetermined number of cycles of the phase spectrum and, when signals are contaminated by higher modes, for the difficulty of isolating the fundamental mode (Nunziata, 2005).

Seismic noise is everywhere and ever present and, due to its non invasive application, seems to be the next challenge in geophysics.

We applied these topics on the northern part of venetian plain (North Italy), in a studied area of circa 180 km².

The aim of the study was to define shear wave structural models of subsoil, useful for a deterministic hazard scenario. For this aim, after a literature study, several experimental works are developed:

- earthquakes recording
- controlled source seismic surveys
- seismic noise single station acquisitions
- seismic noise array cross- correlation experiments.

In the past, the area in exam was studied for gas and water exploitation but no shear waves informations were available. Reflection seismic prospecting and deep wells were however useful for subsoil geometry study, for our techniques validations and comparison.

The study of Rayleigh dispersion using FTAN involves earthquake records, controlled source seismic experiments and seismic noise analysis.

Earthquakes recording was mainly used for analyze different site response for

local events, and to study deep bedrock shear velocities.

Controlled source seismic experiments involves the study of Rayleigh dispersion to infer upper subsoil shear wave velocities.

Several types of source were tested:

- TNT
- heavy wight drop
- seismic gun
- hammer

The use of TNT allowed to reach 100 m depth investigation and to develop an attenuation study in the northern part of the studied area. The controlled source methods results gave accurate shear waves structural models of the upper subsoil for the area.

Seismic noise single station acuirements were performed in the entire studied zone. Horizontal to Vertical Spectral Ratio technique (H/V) gave us informations on the fundamental period of subsoil and buildings. No shear waves or amplification factors are taken into account with this methodology, that remain in author's opinion with strong theoretical limitation and doubts.

The experiments underlined that it is fast and cheap methods to detect subsoil fundamental period, and that it could be useful for a subsoil homogeneity definition in wide unknown areas. However synthetic test proven the Rayleigh predominantly contribute in seismic noise. This implies we can not infer subsoil shear waves by easy assumption as SH transfer function. The amplitude of H/V peaks are strong related to the impedance contrasts in the subsoil, even if more than one. Relate it directly to seismic hazard appears not possible and sure unsuccessful. It is author's persuasion that this methodology still remains a valid but qualitative application of seismic noise, moreover clear theoretical explanations of presumed (and unfortunately diffuse) applications still lack.

A seismic noise cross correlation study was also performed. We computed time cross correlation of seismic noise between 2 mobile stations in several conditions, in order to infer media Green Function. Many records were useless, cause no coherent noise appear in the NCF (noise cross- correlation function). We obtained good results in few cases: for short stations inter- distance, in presence of

directional seismic noise source, and for long station inter- distance in case of (rare) diffuse noise field. For our long period recordings only few days gave us the attended results. If we believe that 6 months of recordings work risk to be complete unsuccessful, we can consider it a not repeatable experience. But for short inter distance condition, in presence of detected noise sources, we evaluated a Shear wave model till 130m depth with very cheap and easy experiments. We consider this a great improvement for seismic scenario study, where no shear wave model is known, and the local conditions permit its application. For long period recording we think that only existing networks are useful. Fixed Networks, or mobile arrays also, installed for Earthquake recordings or Volcanoes monitoring, could be successful used for this purposes. If continuous recordings stop to be useless 'noise' and become useful signals, a new topic for earth interior study could be developed. Signal computed is often hard to construe, but computation of particle motion and, above all, correlations with known subsoil velocities, can be helpful. In conclusion, considering that even in developed country shear velocities of soil are often unknown, this methodologies could be a modern answer, preferable to many literature uncertain correlation data.

Thanks to the experimental work described, we were able to define one shear wave structural model for the northern part of our test site, one for the central part and one for the southern part. This shear wave definition was necessary for our aim: a seismic hazard study.

This Thesis final result is a deterministic seismic hazard scenario of the studied area. Two of the strongest historical earthquakes, that involves the territory in exam, were taken as sources for a complete deterministic ground motion computation. The 3 components virtual receivers recordings, thanks to the shear wave structural model obtained, gave us a complete and realistic seismic motion description, useful for seismic Engineering needs.

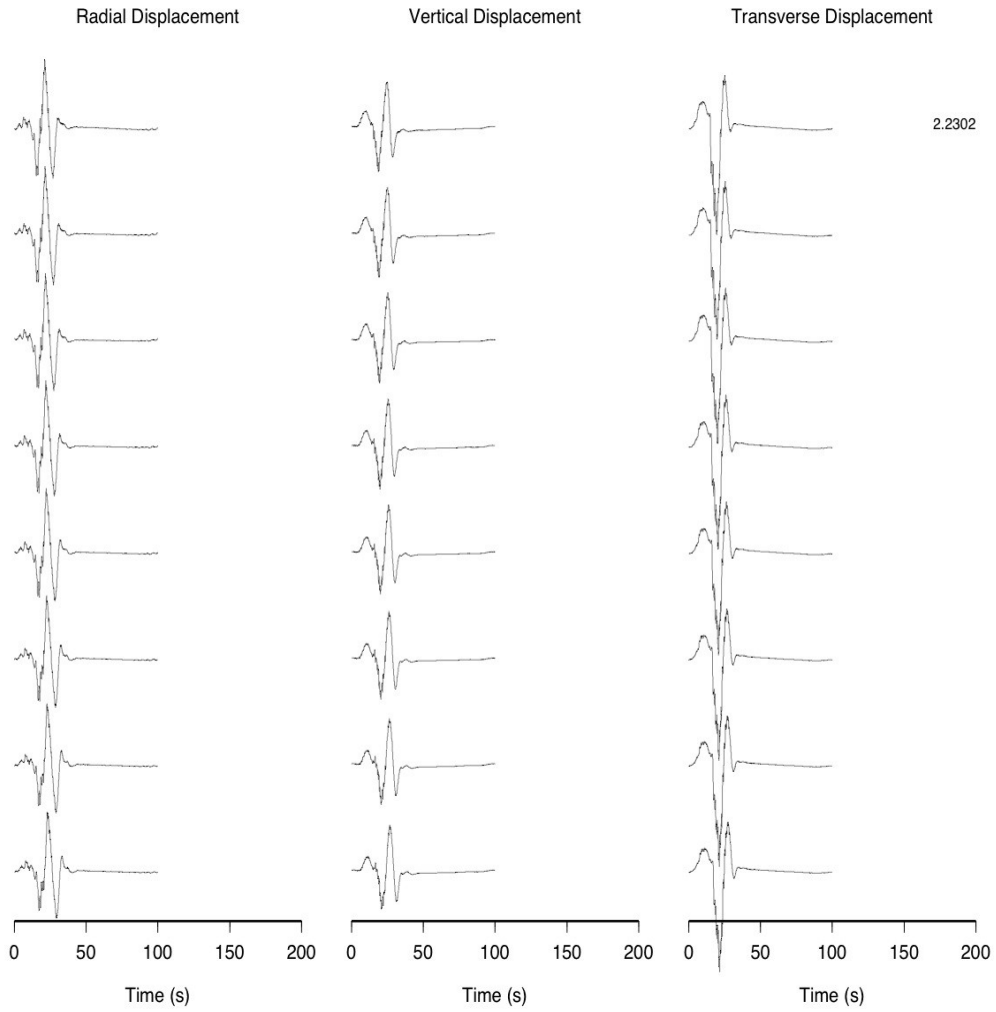
APPENDIX 1

Synthetic Seismograms

APPENDIX 1
Deterministic Scenario

CANSIGLIO EARTHQUAKE SCENARIO
DISPLACEMENT

from station 1 to station 8 (see chap 6 for details)

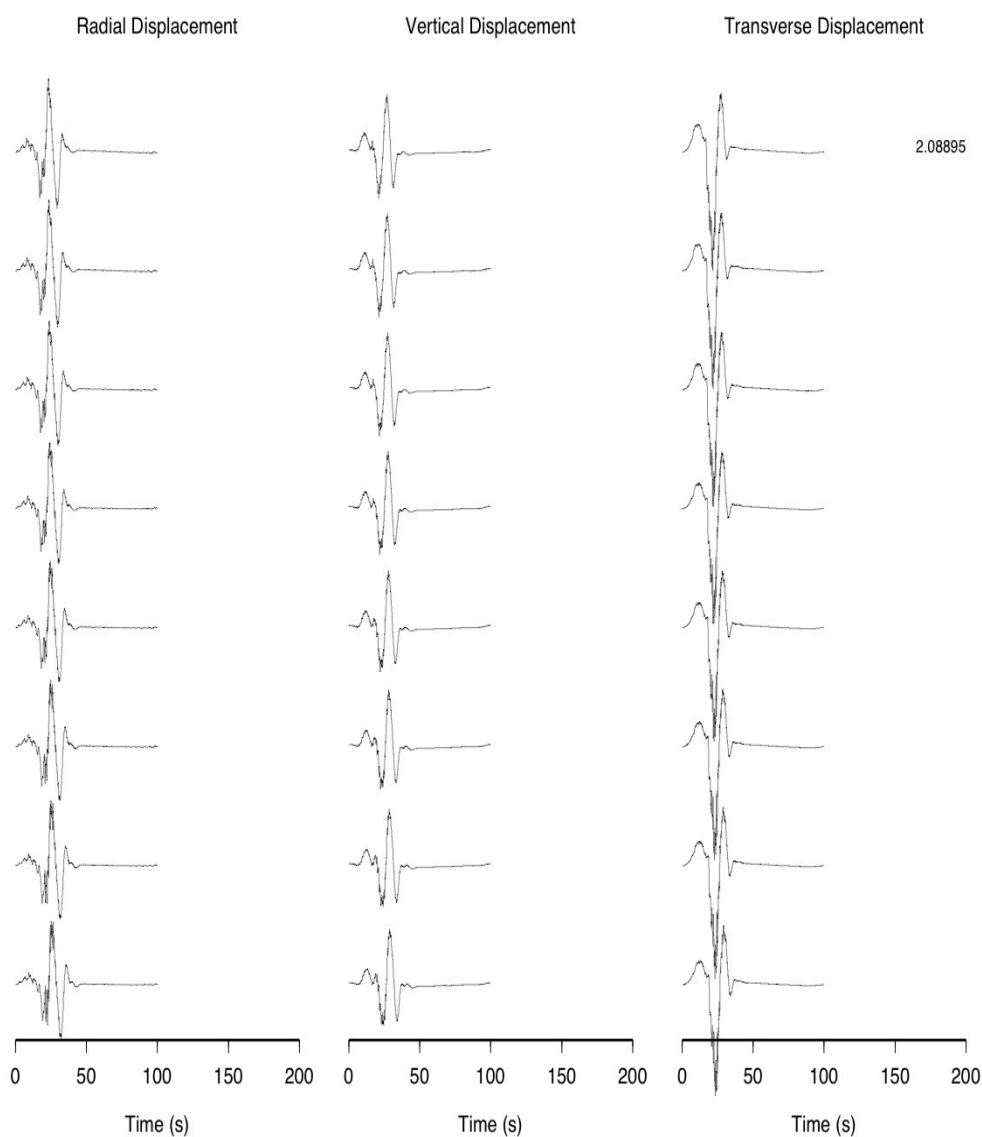


Deterministic Scenario

CANSIGLIO EARTHQUAKE SCENARIO

DISPLACEMENT

from station 8 to station 16 (see chap 6 for details)

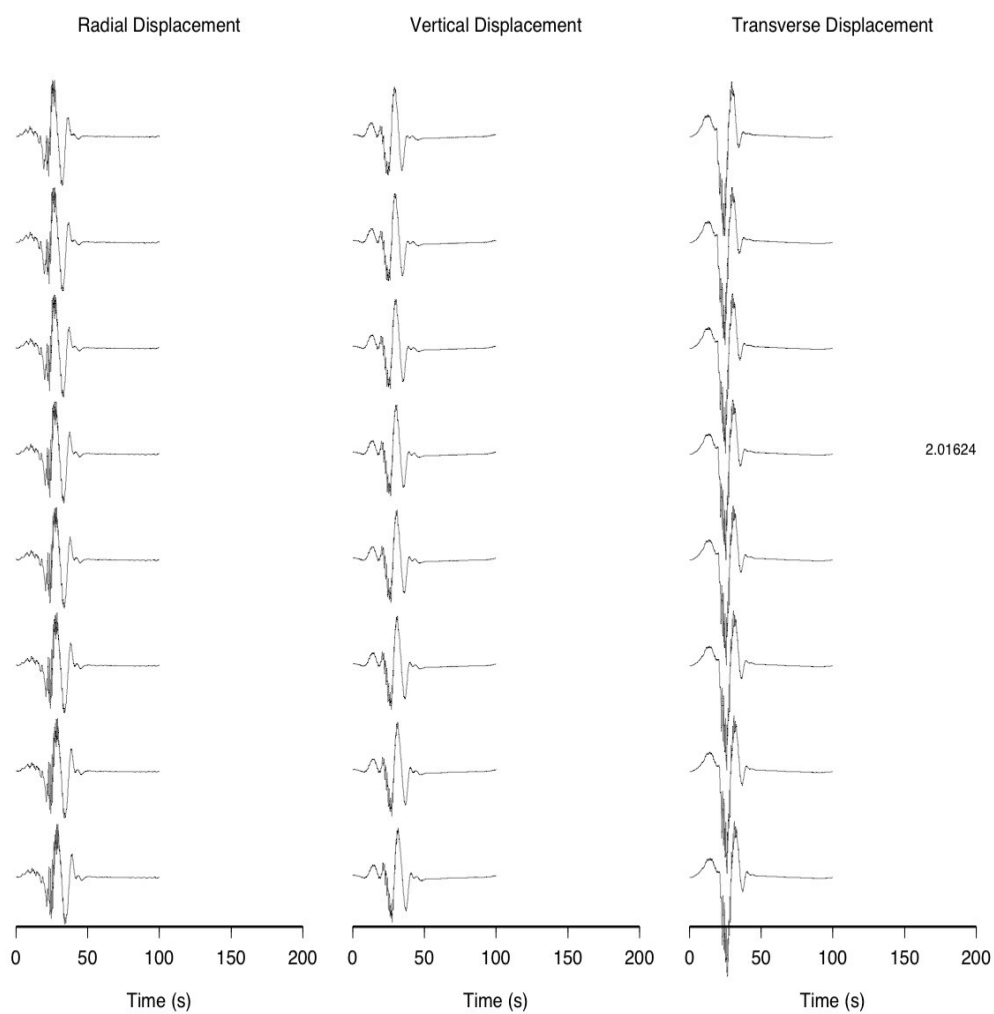


Deterministic Scenario

CANSIGLIO EARTHQUAKE SCENARIO

DISPLACEMENT

from station 16 to station 24 (see chap 6 for details)

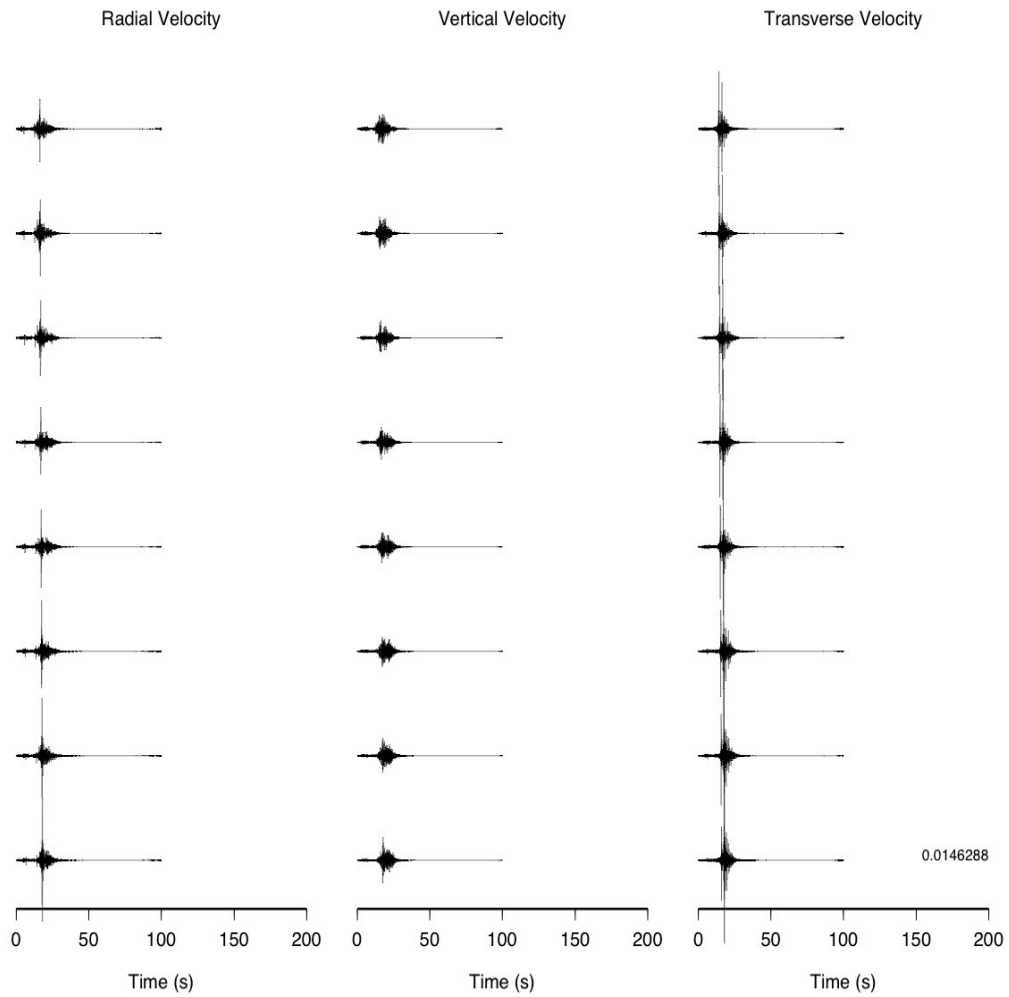


Deterministic Scenario

CANSIGLIO EARTHQUAKE SCENARIO

Velocity

from station 1 to station 8 (see chap 6 for details)

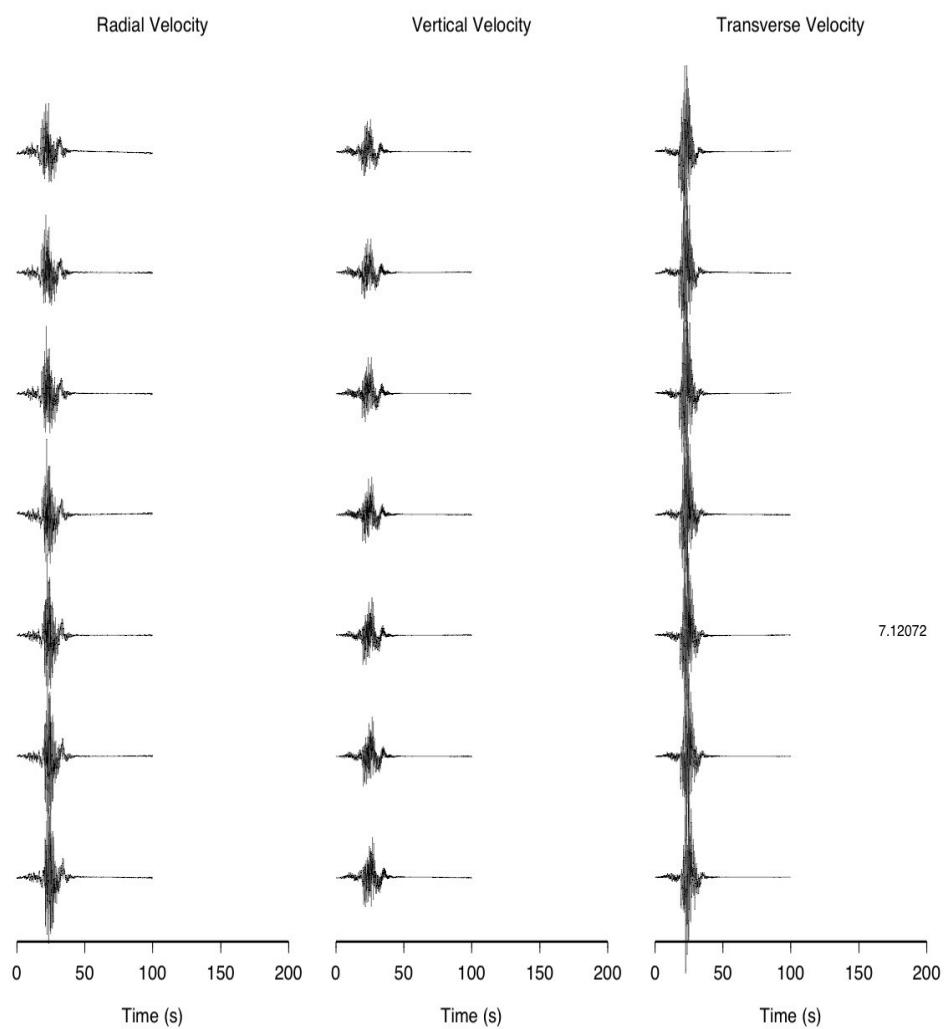


Deterministic Scenario

CANSIGLIO EARTHQUAKE SCENARIO

Velocity

from station 8 to station 16 (see chap 6 for details)

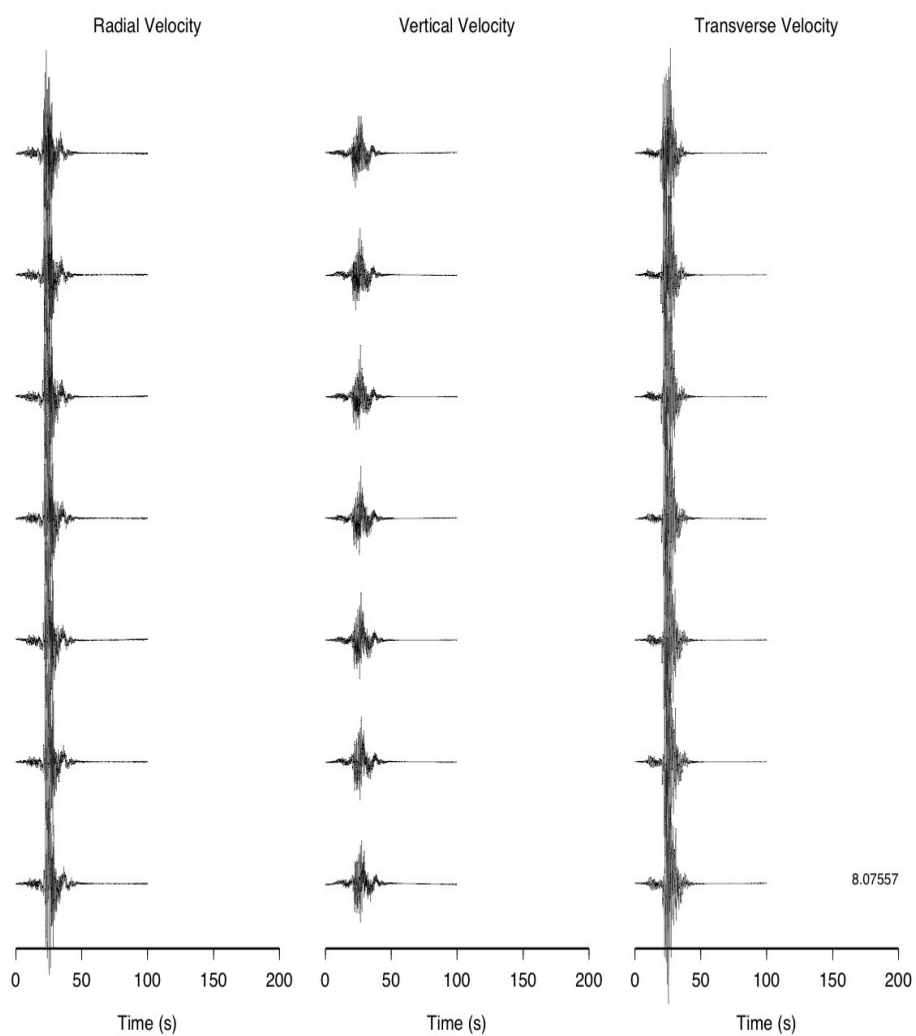


Deterministic Scenario

CANSIGLIO EARTHQUAKE SCENARIO

Velocity

from station 16 to station 24 (see chap 6 for details)

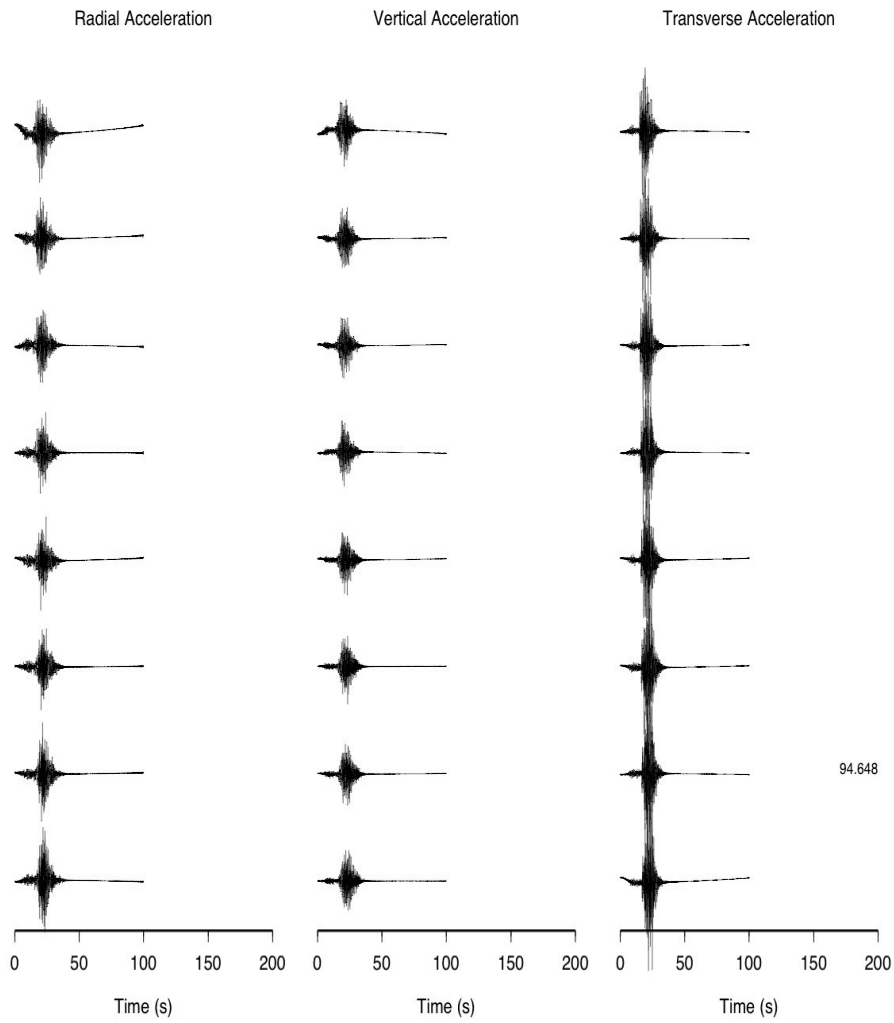


Deterministic Scenario

CANSIGLIO EARTHQUAKE SCENARIO

ACCELERATION

from station 1 to station 8 (see chap 6 for details)

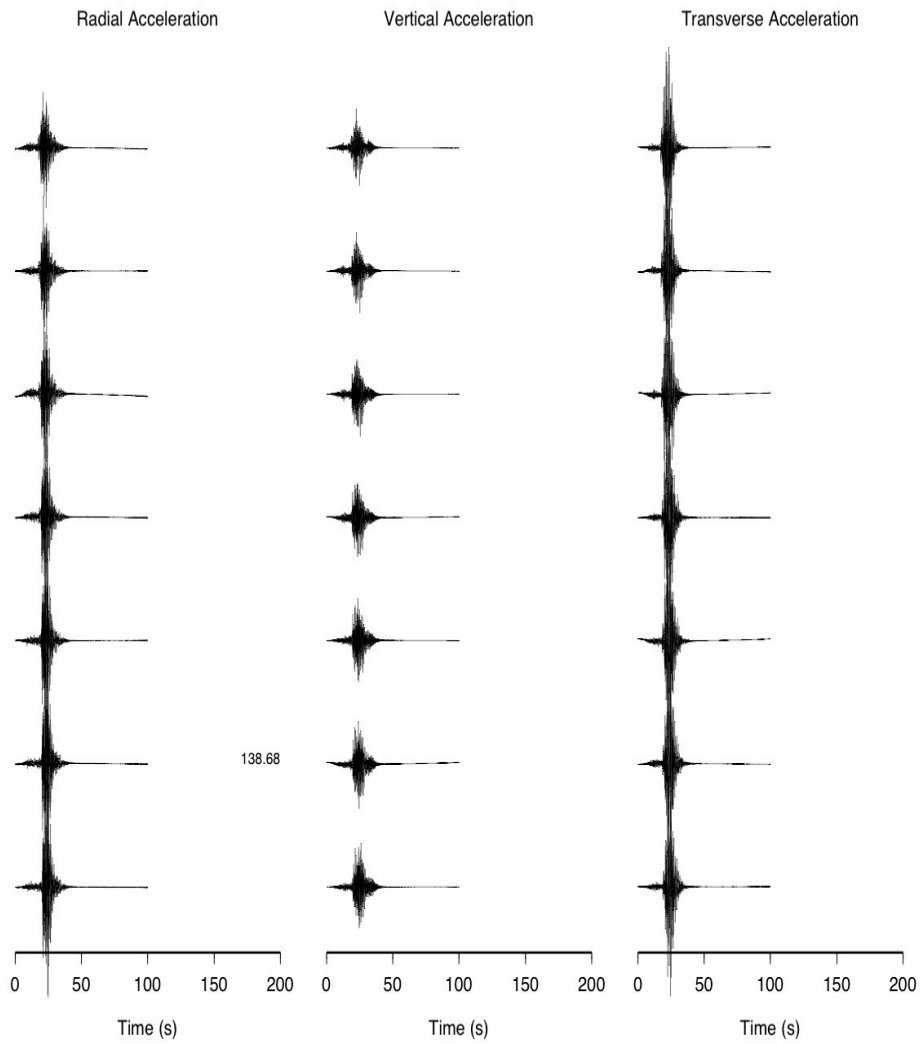


Deterministic Scenario

CANSIGLIO EARTHQUAKE SCENARIO

ACCELERATION

from station 8 to station 16 (see chap 6 for details)

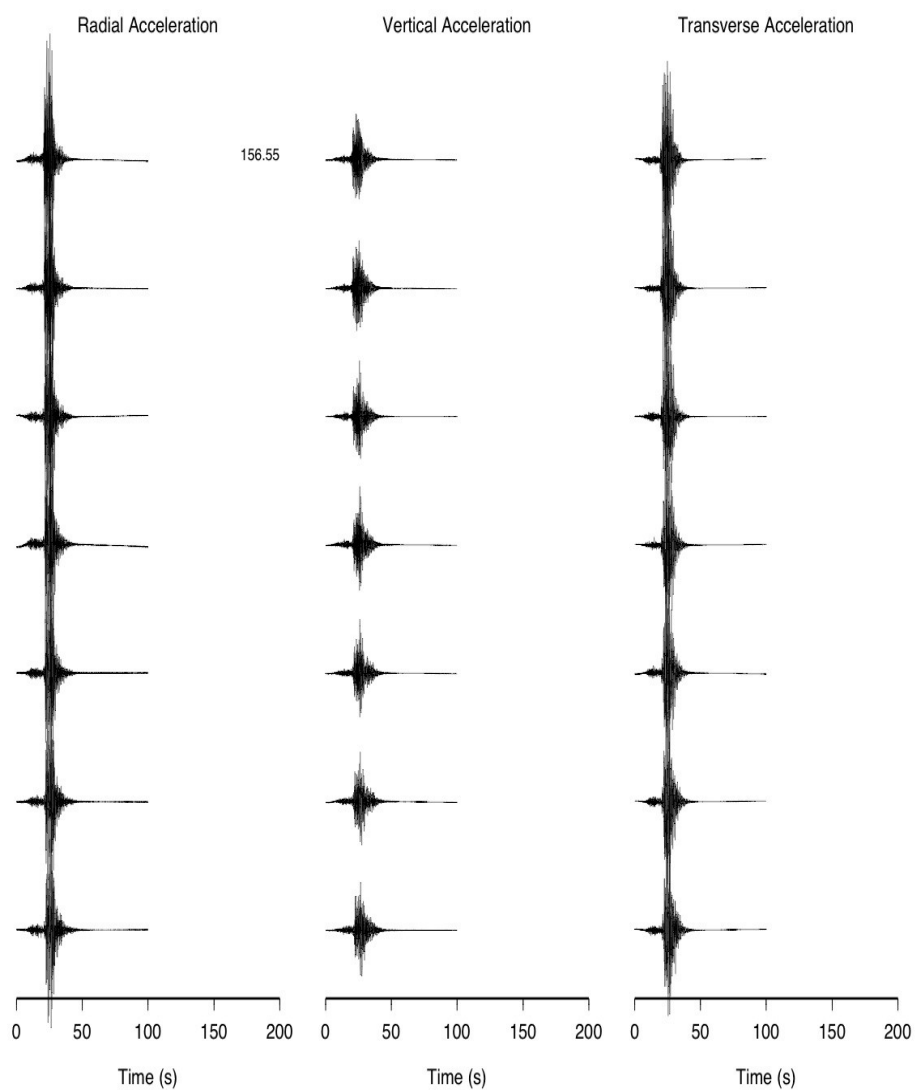


Deterministic Scenario

CANSIGLIO EARTHQUAKE SCENARIO

ACCELERATION

from station 16 to station 24 (see chap 6 for details)

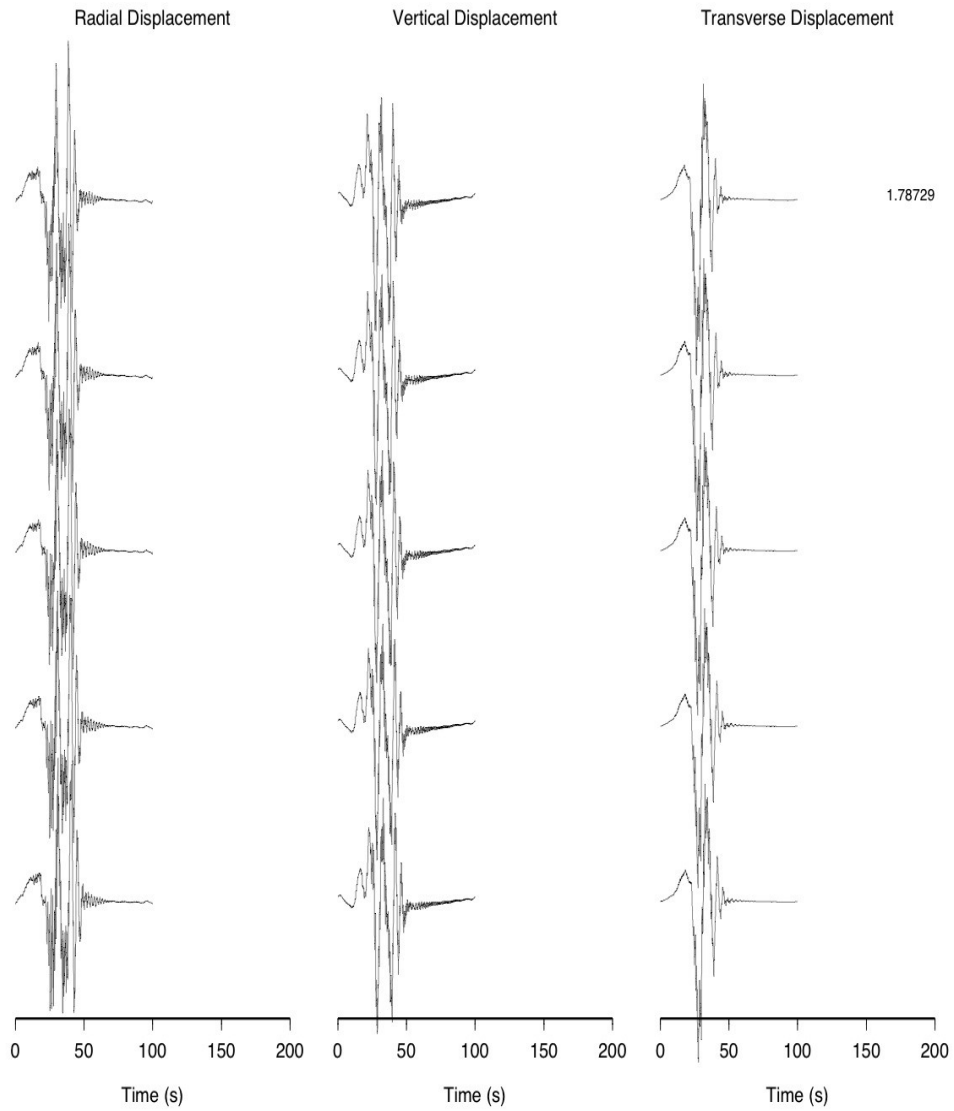


Deterministic Scenario

MONTELLO EARTHQUAKE SCENARIO

DISPLACEMENT

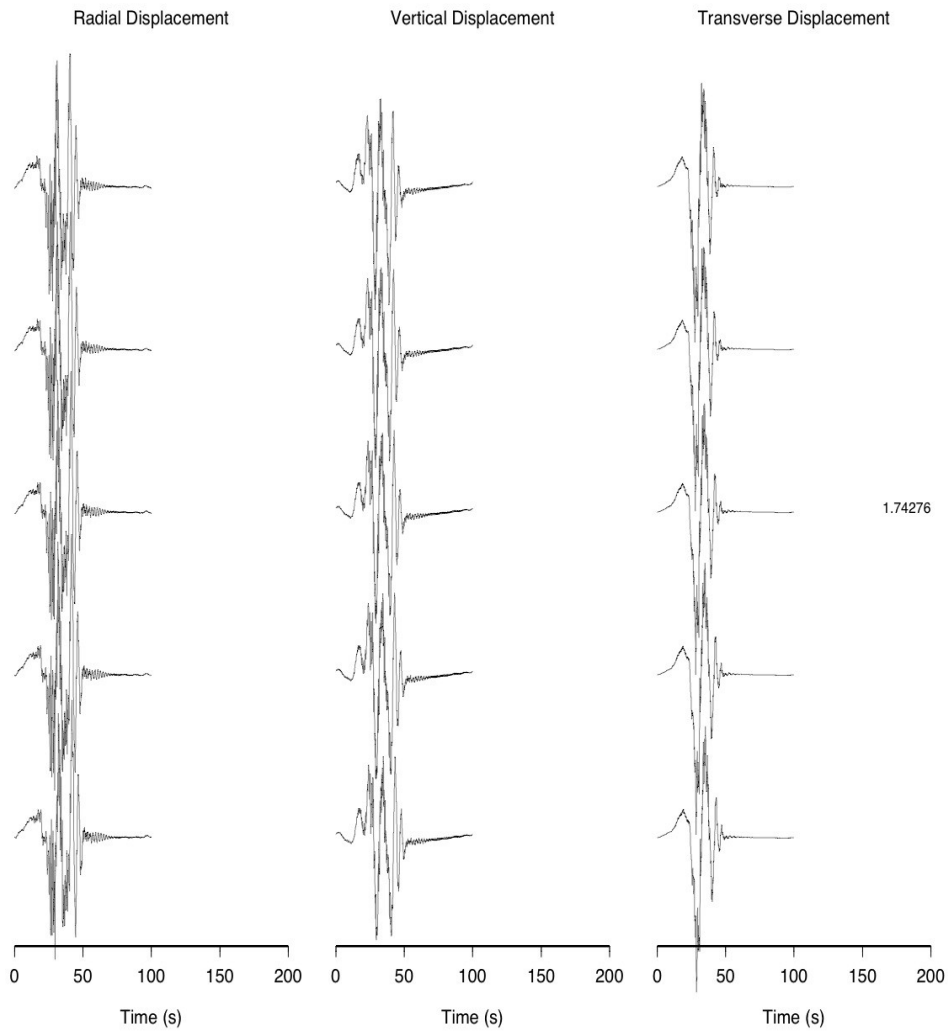
from station 1 to station 5 (see chap 6 for details)



Deterministic Scenario

MONTELLO EARTHQUAKE SCENARIO
DISPLACEMENT

from station 6 to station 11 (see chap 6 for details)

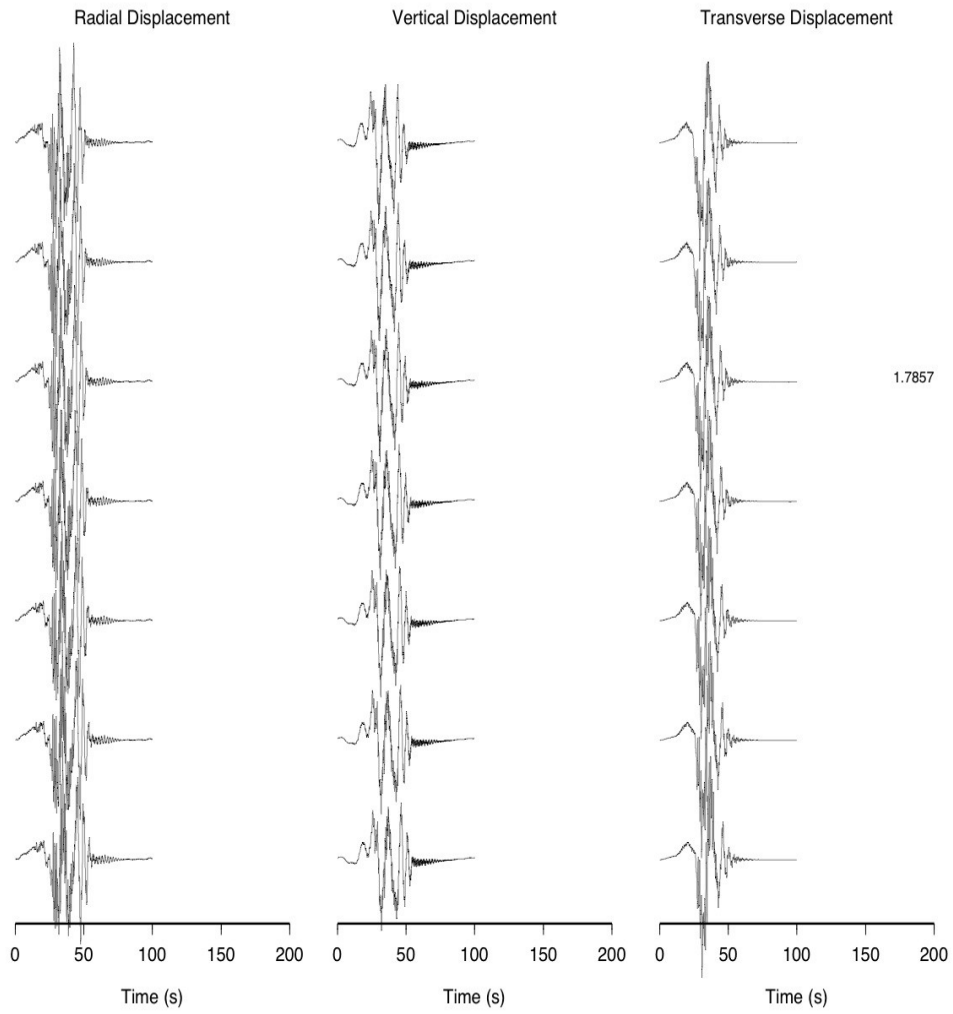


Deterministic Scenario

MONTELLO EARTHQUAKE SCENARIO

DISPLACEMENT

from station 12 to station 17 (see chap 6 for details)

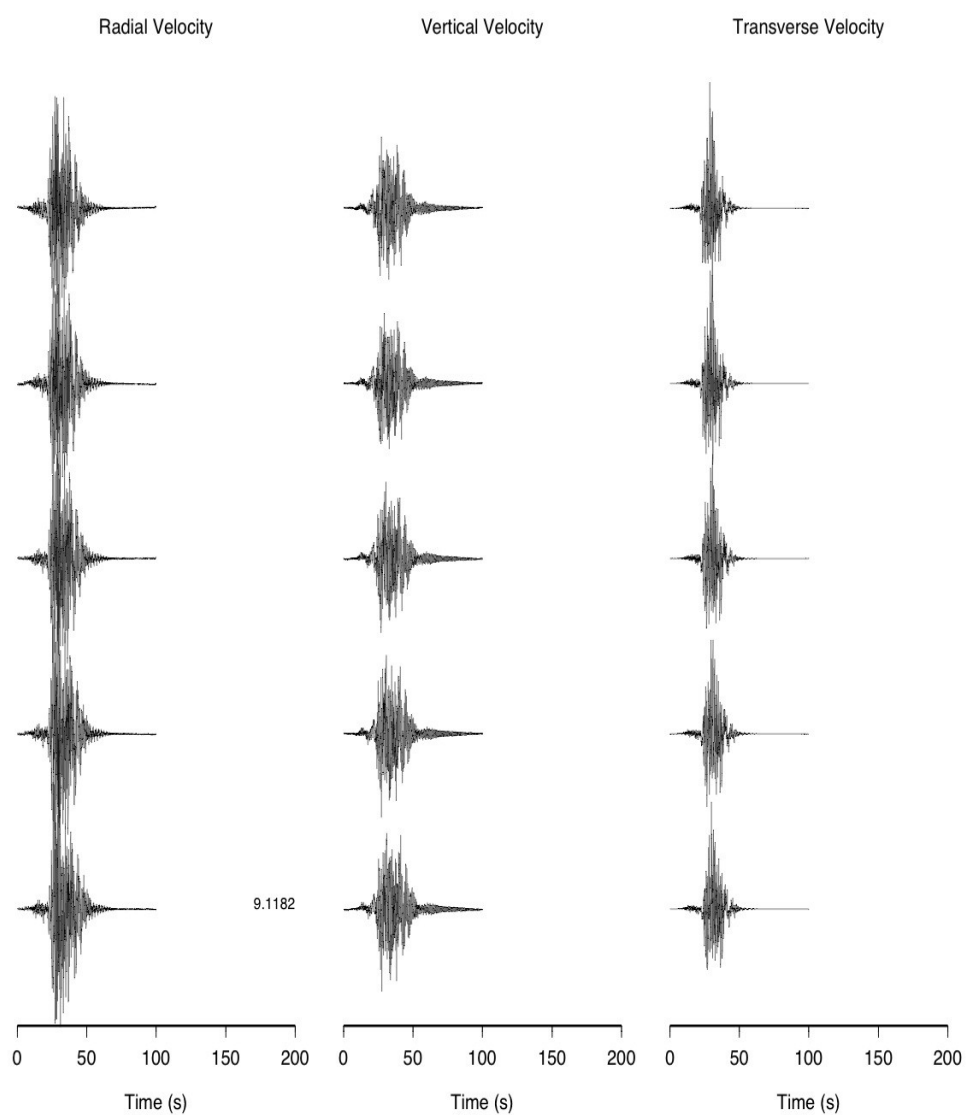


Deterministic Scenario

MONTELLO EARTHQUAKE SCENARIO

VELOCITY

from station 1 to station 5 (see chap 6 for details)

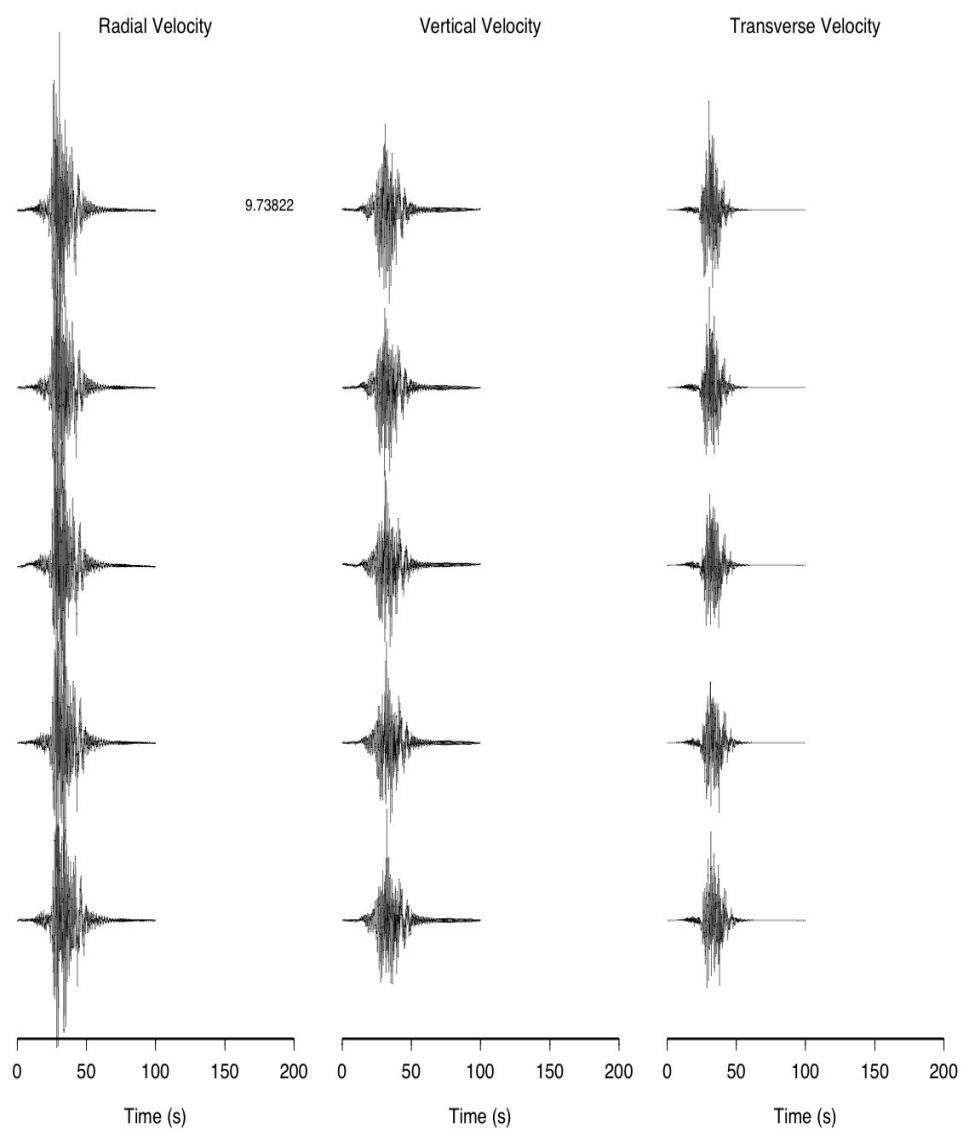


Deterministic Scenario

MONTELLO EARTHQUAKE SCENARIO

VELOCITY

from station 6 to station 11 (see chap 6 for details)

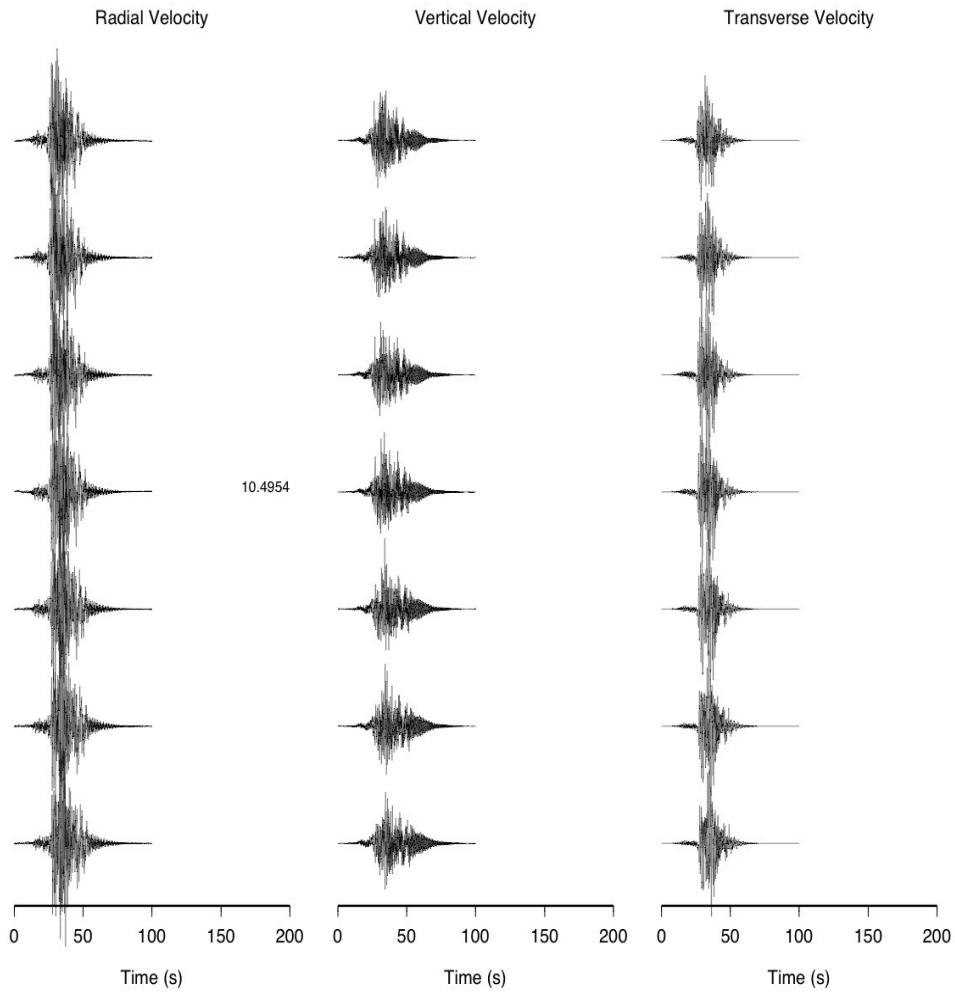


Deterministic Scenario

MONTELLO EARTHQUAKE SCENARIO

VELOCITY

from station 12 to station 17 (see chap 6 for details)

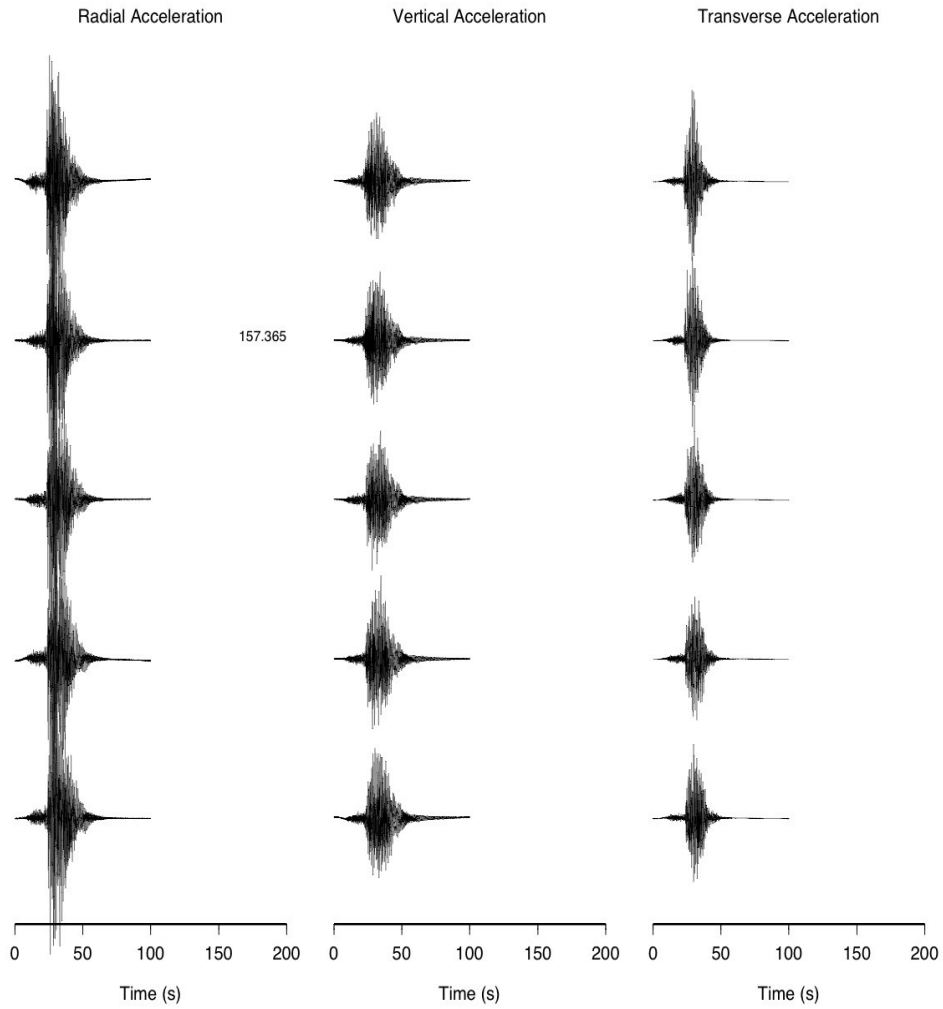


Deterministic Scenario

MONTELLO EARTHQUAKE SCENARIO

ACCELERATION

from station 1 to station 5 (see chap 6 for details)

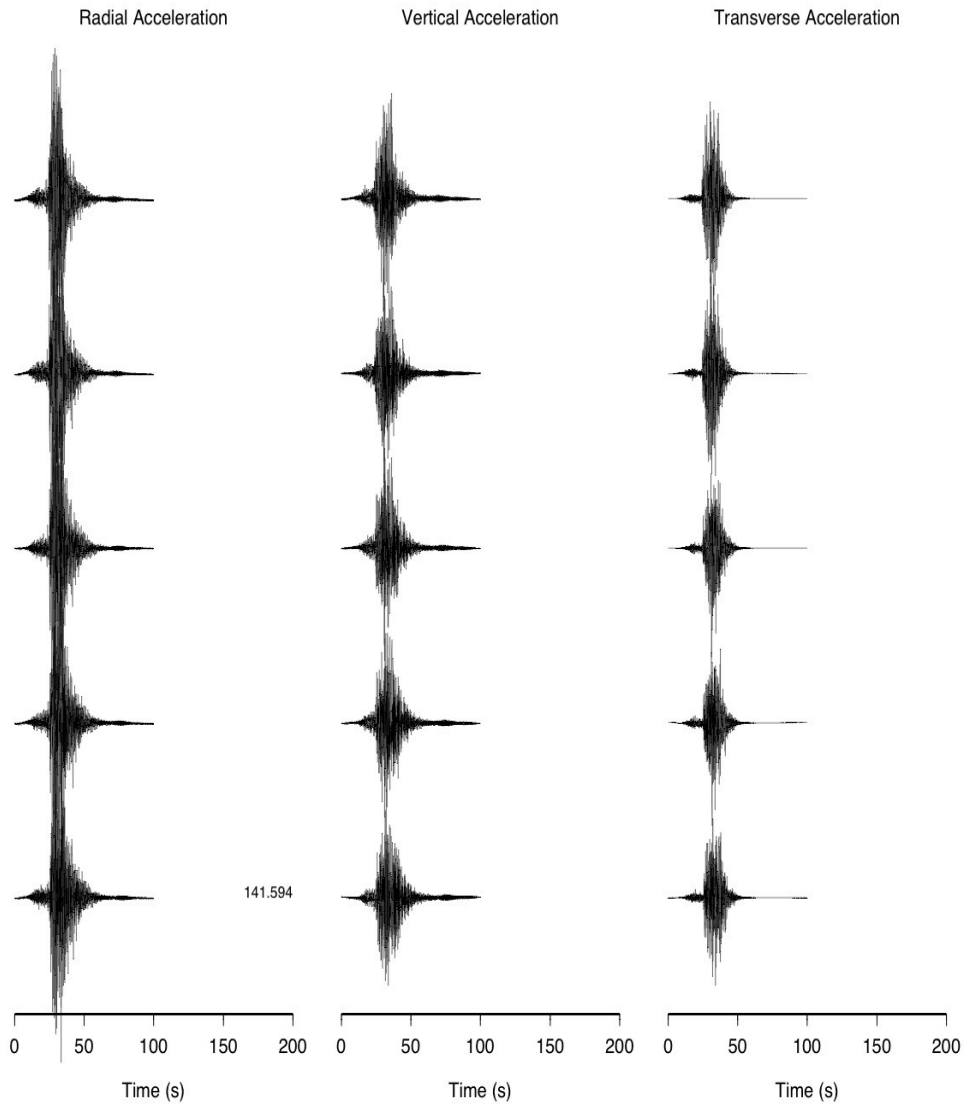


Deterministic Scenario

MONTELLO EARTHQUAKE SCENARIO

ACCELERATION

from station 6 to station 11 (see chap 6 for details)

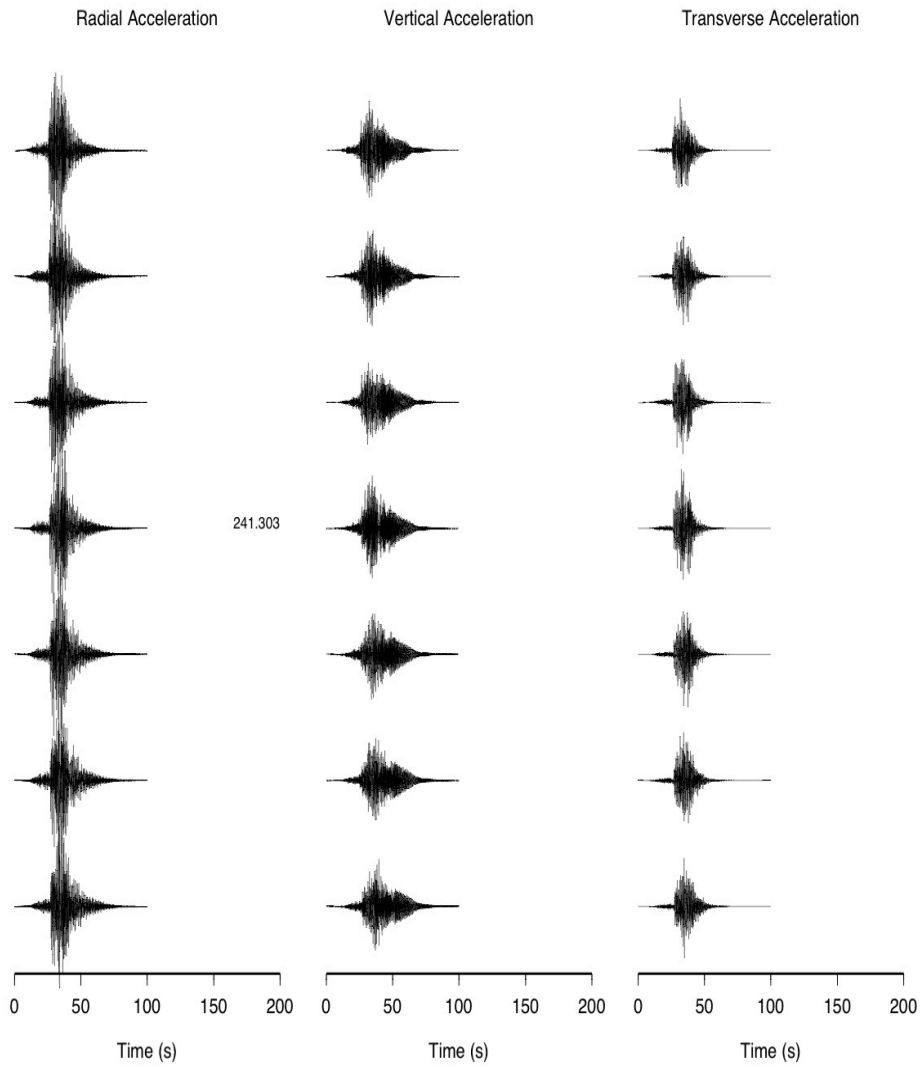


Deterministic Scenario

MONTELLO EARTHQUAKE SCENARIO

ACCELERATION

from station 12 to station 17 (see chap 6 for details)



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