

## VSP processed down-hole data within local seismic response assessment

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### *Utilizzo di dati down-hole con elaborazione VSP nell'ambito degli studi per la valutazione della risposta sismica locale*

**ABSTRACT:** Local effects evaluation may be solved using different methodological ways. VEL Project of Tuscany district approach, foresees the evaluation of the surface effects in a specified zone of a "forecasted" earthquake, through geological, geomorphologic, geotechnical, geophysical and numerical modelling. The knowledge of bedrock depth and geometry is a fundamental issue in such a multidisciplinary integrated approach. Down-hole tests carried out in not sufficiently deep borehole to reach bedrock, have been processed as VSP (Vertical Seismic Profiling) method, allowing the knowledge of bedrock depth. This has been obtained developing a processing aimed to the study of reflected signals that provided important information on discontinuities occurring below the borehole bottom. Results obtained by VSP processing from conventional SH waves down-hole data, have been calibrated by comparison with an high-resolution shear wave reflection line carried out in the same site. This comparison provided new cognitive elements and work prospects.

**RIASSUNTO:** La valutazione degli effetti locali può essere effettuata mediante differenti approcci metodologici. Quello adottato nel progetto V.E.L. (Valutazione degli Effetti Locali) della Regione Toscana, cerca di stimare gli effetti in superficie in una specifica area soggetta ad un terremoto di riferimento, attraverso indagini geologiche, geomorfologiche, geotecniche, geofisiche e modellazione numerica. La conoscenza della profondità e della geometria del substrato sismico è di fondamentale importanza in un approccio multidisciplinare ed integrato di questo tipo. Dati down-hole acquisiti in sondaggi non sufficientemente profondi da interessare il bedrock, sono stati trattati mediante un'elaborazione VSP (Vertical Seismic Profiling) con la finalità di ricavare la profondità del substrato sismico. Tale risultato è stato raggiunto sviluppando un processing adeguato, finalizzato allo studio dei segnali riflessi che, come è noto, forniscono importanti informazioni sulle discontinuità presenti ad una profondità maggiore di quella del fondo-foro. I risultati ottenuti in questo modo sono stati successivamente tarati mediante un'indagine di sismica a riflessione ad alta risoluzione in onde di taglio, effettuata nello stesso sito. L'analisi comparativa dell'indagine sismica a riflessione con i VSP fornisce utili spunti di discussione.

**Key terms:** Local seismic response, VSP, Down Hole, Reflection seismic

**Termini chiave:** Valutazione degli effetti locali, VSP, Prova down-hole, Sismica a riflessione

### 1. Introduction

Knowing the depth and the geometry of the bedrock for the characterization of local seismic response is of great importance when using analytical methods (Celebi, 1995; Bellucci et al., 1998; Coetzee et al., 1995; Idriss et al., 1973; Itasca Consulting Group, 2000; Pergalani et al., 1999; Ferrini et al. 2001; D'Intinosante, 2003; Signanini et al., 2003). The VEL Project of Tuscany district approach, foresees the evaluation of the surface effects in a specified zone of a "forecasted" earthquake, through geological, geomorphologic, geotechnical, geophysical methods and numerical modelling.

Normally, in areas of very thick covering deposits, the depth of the bedrock is determined based on the surface

geology. Even if geognostic bore holes instrumented for down hole investigations are available (for measuring the Vs and for calculating the Vs30 according to the Italian Ordinance P.C.M. 3274/03), they rarely reach depths near the bedrock due to excessive costs. On the other hand, within these contexts, refraction seismics would be of little use due to the excessive depths that generally need to be reached. Even high resolution reflection seismics, which is by far the most appropriate, has prohibitive costs in most cases.

This work proves that when down hole data is available it is possible to determine the depth of the bedrock within a certain margin of error, even though it has not been reached by the drilling of the bore holes. This can be obtained by

VSP (Vertical Seismic Profiling, Hardage, 1983; Mari et al., 1998, Signanini et al., 2001, Signanini & Torrese, 2004) processing of the data obtained with classical down hole techniques, without additional costs for other investigations. However, this implies that all seismic signals be adequately processed and not only the first arrivals. As a matter of fact, even the analysis of the reflected signals in a hole record can significantly contribute to the definition of underground geometry. This can be obtained from down-hole data with long acquisition times and short intervals of measurement. In the framework of the VEL (Local Effect Evaluation) project (Rainone et al., 2003; Regione Toscana, 2000) of Tuscany Region for reduction of seismic risk, data from down-hole tests with SH waves have been processed (Signanini et al., 2001) to define bedrock depth and geometry. New software was developed for this purpose to isolate and correct the reflected signals.

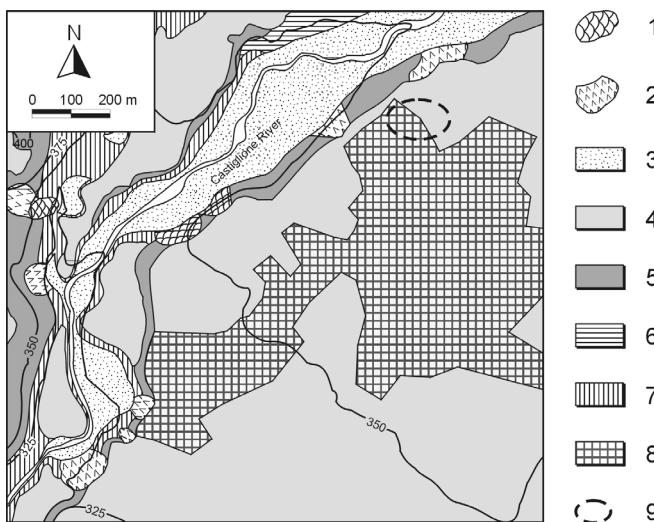


Fig. 1. Geological-geomorphological scheme of Pieve Fosciana test site. 1) active landslides 2) dormant landslides (Quaternary); 3) recent alluvial deposits (Quaternary); 4) morphological flat of fluvial origin with or without alluvial deposits (Quaternary); 5) pebbles mostly made by quartz-feldspar "Macigno" sandstones (Quaternary-Pleistocene); 6) sands and clays with lignite levels (middle-upper Pliocene); 7) alternance of quartz-feldspar sandstones, shale (middle-upper Oligocene-upper Oligocene); 8) urbanized area; 9) survey site. By NARDI et al. (1987, modified)

*Carta geologica-geomorfologica dell'area di Pieve Fosciana 1) frane attive 2) frane quiescenti (Quaternario); 3) depositi alluvionali recenti (Quaternario); 4) spianate morfologiche di origine fluviale con o senza depositi alluvionali (Quaternario); 5) ciottoli a prevalenti elementi di arenaria "Macigno" (Quaternario-Pleistocene); 6) sabbie e argille lignitifere (Pliocene medio-superiore); 7) arenarie quarzoso-feldspatiche alternate ad argilliti e siltiti (turbiditi, Oligocene medio-superiore-Oligocene superiore); 8) area urbanizzata; 9) sito d'indagine. (Da NARDI et al., 1987, modificato)*

Once sections similar to reflection stack sections are obtained (i.e., with horizontal reflected signals), the results are compared with those obtained by high-resolution SH

waves surface reflection seismic carried out on the same site. In this work we discuss the techniques used and the results obtained.

## 2. Geological-technical features of the area

The test site (Fig. 1) is located within the Pieve Fosciana village (Tuscany, Italy) on a morphological flat of an alluvial terrace. It is located on the left of the Castiglione stream (Serchio river basin).

The outcropping geological units can be summarised as follows (Fig. 2; Boccaletti & Coli, 1985; Cancelli et al., 2000; Eva et al., 1978; Nardi et al., 1987):

### Tuscan nappe:

*Macigno (mg):* alternance of arenaceous turbidites made of quartz-feldspar sandstones and shale. (middle-upper Oligocene – upper Oligocene)

### Lacustrine and fluvial deposits:

*(arg):* clays and grey sands, sandy clays and clayey sands, with levels of gravels in clayey-sandy matrix; clays host vegetable remains, organic and lignite levels (medium – upper Pliocene)

### Quaternary deposits:

*(ct/mg):* ancient terraced alluvial deposits, including monogenic gravels made by arenaceous pebbles (Macigno) in red-ochre sandy matrix, often located on a multiple terrace order (medium-upper Pleistocene)

*(dt):* detritus and cover (Quaternary)

*(all):* recent alluvial deposits (Olocene)

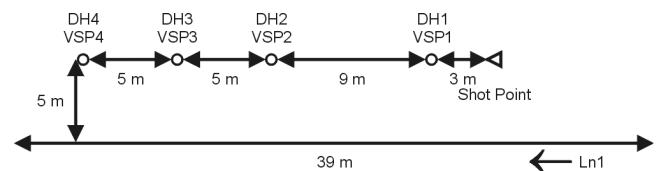


Fig. 2. Survey scheme: Ln1 = reflection line; DH1 = down-hole; VSP1 = vertical seismic profiling

*Schema delle indagini geofisiche effettuate: Ln1 = linea sismica a riflessione; DH1 = prova down-hole; VSP1 = vertical seismic profiling*

## 3. Geophysical prospections

### 3.1 Acquisition

Four geognostic boreholes, all instrumented for down hole investigations, were present on the Pieve Fosciana site. However, none of them had reached the bedrock. All data acquired with classic down holes procedures (for the dynamical characterization of lithologies in terms of  $V_p$  &  $V_s$ ) have been processed as VSP so as to define the depth of the Macigno formation (seismic bedrock). One SH wave high-resolution reflection line was acquired to calibrate the results obtained from the VSP (survey scheme reported in Fig.2).

The acquisition parameters of the down-hole tests and

the reflection line are summarized in tab. 1.

SH waves have been used in both tests. As known, the SH waves velocity is closely related to the dynamic shear module  $G=\rho V_s^2$ , fundamental for seismic behaviour modelling. Moreover, in the context of porous deposits, using SH waves is preferable since they are unaffected by saturation. In presence of nearly horizontal stratification, SH waves, differently from longitudinal P and transversal

SV waves, are not affected by transmutations. Then, given a frequency spectrum, shear waves have, in respect to longitudinal ones, a lower velocity and lower wavelength, and consequently higher resolution (Signanini & Torrese, 2004). They also show a lower attenuation in unsaturated media and the attenuation is less influenced by saturation (Nur et al, 1969; Winkler et al, 1982).

Table 1. Acquisition parameters for DH1, DH2, DH3, DH4, LN1

*Parametri d'acquisizione delle indagini sismiche DH1, DH2, DH3, DH4, LN1*

DH 1	DH 2	DH 3	DH 4	LN1
Source: SH waves				
Instrument: EG&G Strata View a 16 bit	Instrument: EG&G Strata View a 24 bit			
Sampling rate: 0.5 ms				
Recording lenght: 256 ms	Recording lenght: 256 ms	Recording lenght: 256 ms	Recording lenght: 256 ms	Recording lenght: 1024 ms
Offset: 3 m	Offset: 12 m	Offset: 17 m	Offset: 22 m	Offset: 3 m
Measure interval: 1.5 m	Measure interval: 1.5 m	Measure interval: 1.5 m	Measure interval: 1.5 m	Spread: off-end push increase Fold: 600 %
Max depth: 79 m	Max depth: 33.5 m	Max depth: 49 m	Max depth: 79 m	Group interval: 1 m Shot interval: 1 m

Energizing was obtained by hammering on the sides of a heavy box, perpendicular to the seismic line and well coupled to the ground (Palestini et al, 1988). The holes have been instrumented simultaneously to the energization in the same point (variable offset). Along the reflection line (Milkeret et al, 1986), the receiving system, with a total of 12 channels, was composed by an array of 5 horizontal geophones per channel, perpendicular to the line and connected in parallel to obtain an analogical filtering (Stumpel, 1984).

The small geophone spacing (1 m) is justified by the need of having a high number of CDP for length unit (Knapp et al, 1986), considering the extreme heterogeneity of the alluvial materials. Stacking was favoured by keeping the arrays short and, given the low depth of the objective, a low coverage was enough to get a good signal-noise ratio (Mari et al, 1998).

### 3.2 Processing and results

Considering that the drillings did not reach the bedrock, the down-hole data have been processed to detect reflections from markers located below the borehole bottom.

The reflected events of a down-hole recording (up going waves) are not easily detected due to interferences of up going and down going trends (Mari et alii, 1990); consequently, a software has been developed to perform, beyond conventional seismic processing, geometric operations and horizontal band filtering (Signanini et al, 2001).

Table 2. Processing sequence for VSP1

*Sequenza di processing dell'indagine sismica VSP1*

VSP1Sx Processing Parameters
01 - AGC: W. L. 425 pt
02 - Normalisation
03 - Filter Hi-Cut: 178 Hz
04 - Linear Gain: 20 db
05 - SSC: $\Delta T=34$ ms; $\Delta C=274$ c
06 - STR: $\Delta T=34$ ms; $\Delta C=274$ c
07 - ASR
08 - HBF
09 - Spike Deconvolution: O.L. =64 pt; P.=0.1%; P.L. =0.125 ms
10 - Filter Hi-Cut: 178 Hz
11 - Linear Gain: 20 db
12 - STR: $\Delta T=13$ ms
13 - ASR
14 - HBF
15 - SSC: $\Delta T=55$ ms; $\Delta C=441$ c
16 - STR: $\Delta T =55$ ms; $\Delta C=441$ c
17 - ASR
18 - Predictive Deconvolution: O.L. = 64 pt; P.=0.1%; P.L. =10 ms
19 - Filter Hi-Cut: 178 Hz
20 - Linear Gain: 10 db

It was thus possible to remove unwanted signals from the seismogram: direct down going waves and all multiple events produced by the seismic markers located over the

geophone and the upgoing surface waves (reflected) and transmuted have been deleted by using geometric and cross-correlation functions plus a subsequent filtering for horizontal bands. After computing the inclination of reflected SH following the last static correction (in the original seismogram the inclination is the same, with opposite dip to the direct, Fig. 3) the final sections have been obtained by a further geometric correction that was made by horizontalizing the requested signals. In this way, all reflected waves of the recording at several depths with the same inclination, (Fig. 3), have been made horizontal. The processing sequence for VSP1 (similar to the other VSP) is summarized in Tab. 2.

It was appropriate to use this method since the adoption of an f-k filter would have damaged the seismogram indistinctly (it must be noted that reflected waves have an opposite and symmetric trend respect to the direct wave, so generally they don't have a single inclination as shown in Fig. 3).

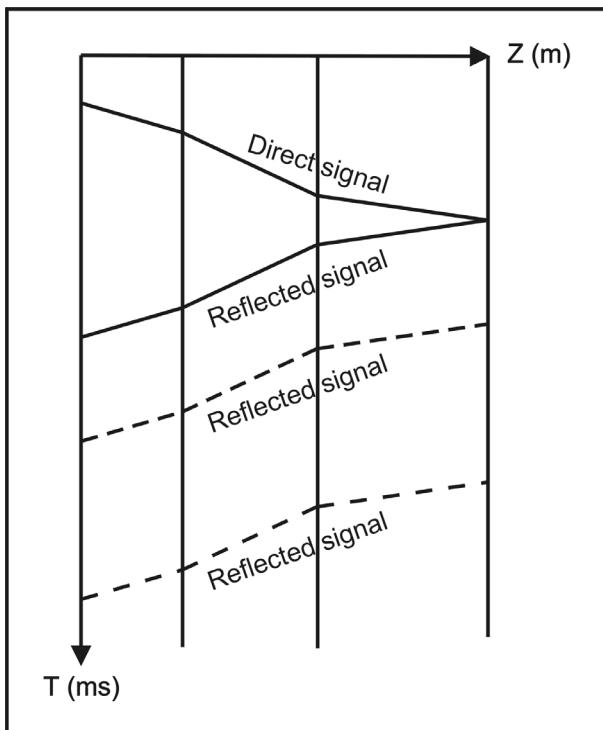


Fig. 3. VSP recording scheme: direct and reflected signals  
Schematizzazione della geometria d'acquisizione e registrazione di un VSP: segnali diretti e riflessi

Figure 4 reports the main processing phases of VSP1; in fig. 5 the final VSP1 section is shown: notice that there are two time scales so that either reflected signals, characterised by two-way times (going and return), or direct ones, characterised by simple times, can be read.

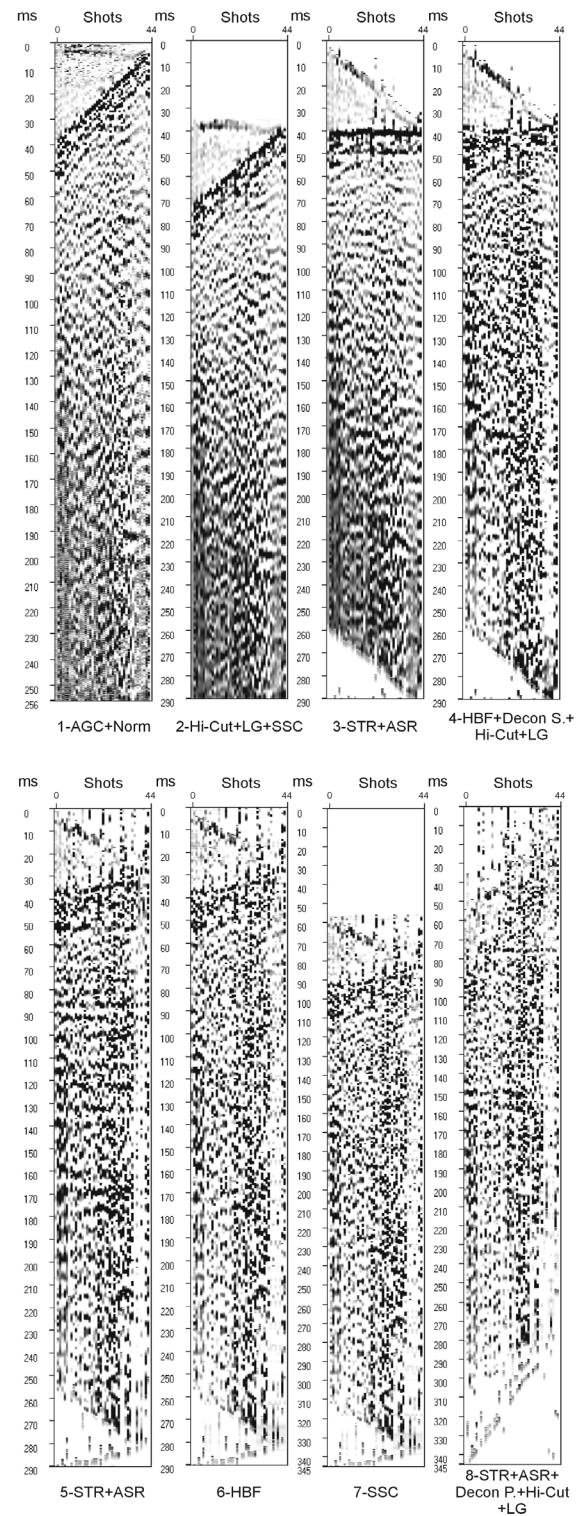


Fig. 4. Main processing phases 1-8 for VSP1: recording acquired with a sample rate of 0.5 ms, have been processed with 8 KHz sample frequency; times have to be multiplied by 4  
Principali fasi di processing 1-8 dell'indagine VSP1: le registrazioni acquisite con un passo di campionamento di 0.5 ms, sono state processate ad una frequenza di campionamento di 8 KHz; i tempi devono essere moltiplicati per 4

The new scales have been calculated by summing the corrections, accumulated during the geometrical operations, to the original scale. There are several reflectors in the sections: even if, in our opinion, almost all the signals are real, it cannot be excluded that the cross-correlation processing, used for obtaining horizontal markers, could have produced false signals. Moreover, the reflections of the markers occurring above the borehole bottom are difficult to be detected due to the fact that direct arrivals are never totally deleted in the same time window.

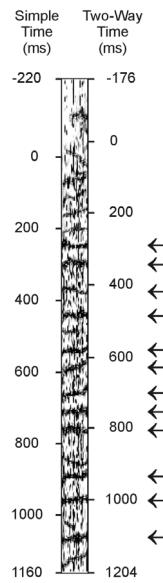


Fig. 5. VSP1 section: notice the two time scales; the arrows point out reflected signals

*Sezione finale VSP1: notare la doppia scala di tempi; le frecce indicano i segnali riflessi*

The test site is characterised by significant heterogeneity and anisotropy, as shown in Fig. 6, where the down-holes are compared by using the velocities derived by the first arrivals. It is, thus, difficult to find correlations among the signals.

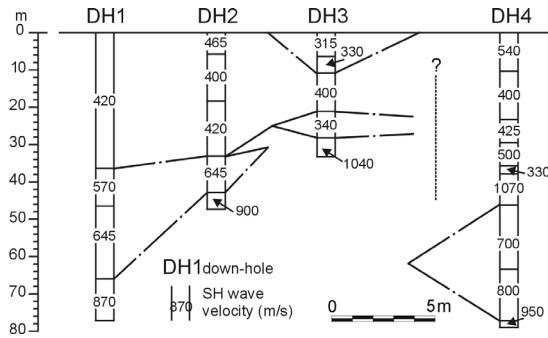


Fig. 6. Correlation between SH waves velocity obtained by down-hole DH1

*Correlazione tra le velocità delle onde SH ottenute dalla prova down-hole DH1*

Accordingly, the results have been compared with the SH waves high-resolution reflection section (Fig. 7) obtained through the processing sequence of tab. 3. Being the occurrence of low-frequency energy consistent, an analysis has been performed to verify the occurrence of Love's waves (first analysis of velocity) and to define better filtering for processing.

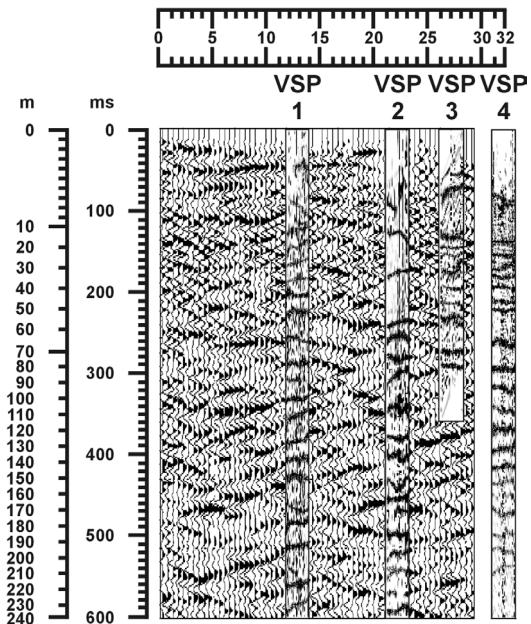


Fig. 7. Superposition of VSP sections over reflection section Ln1  
*Sovrapposizione delle sezioni VSP sulla sezione di sismica a riflessione Ln1*

Table 3. Processing sequence for reflection line Ln1  
*Sequenza di processing della linea sismica a riflessione Ln1*

<b>Ln1S Processing Parameters</b>
<b>Editing</b>
Geometric spreading correction
Trace balancing
Static correction
Sorting
Velocity analysis
F-k filter: Vel -115 m/s, Dip -8.693
Spiking deconvolution: operator length: 64 ms
prediction lag: 0.5 ms
pre-whitner: 0.1 %
Bandpass filter: 30-120 Hz
Velocity analysis
Normal moveout: stretch 0.5
Stack: straight stack
scalar 1
Bandpass filter: 23-114 Hz
Trace scaling: rms amplitude AGC
time gate 307 ms
amplitude 319
trace balancing

There are several reflectors, but it is possible to distinguish a fluvial-lacustrine deposit sector (Fig. 8), with lens and discontinuous geometry, from a bedrock sector where the markers are continuous. Then, an intermediate zone can be interpreted as weathered bedrock (Fig. 9). Several fractures have been also detected.

Depth from ground level m.	Layer thickness m.	Stratigraphic section	Lithologic description	
0	2.9	2.9	Gravels with sandy and sandy-silty matrix	
2.9	5.9	5.9	Sands and silty sands with arenaceous pebbles	
8.8				
70.2		70.2	Silty clays and clayey silt with levels of sands in silty matrix, sandy silt and organic levels	
79		79		

Fig. 8. Stratigraphy from drilling 1 (in which DH1 has been carried out)  
*Stratigrafia ottenuta dal sondaggio geognostico 1 (strumentato per la prova down-hole DH1)*

Although VSP sections show reflections with incidence angle increasing from 1 to 4 (since they are acquired with variable offset, while the reflection section has zero offset), a good correspondence exists between the markers detected by the two methods. It also appears that the geometry of the markers and fractures visible on the reflection section is confirmed in the VSP sections: this should be more valid for VSP 2, 3 and 4, where the lateral investigation is consistent and higher than the horizontal resolution.

The boundaries of the weathered "Macigno" formation, providing important reflectors in sections 2, 3 and 4 (the last one falls out of the area investigated by reflection line) do not give important reflectors in VSP1 (sector A in Fig. 9). This may suggest a gradual transition between the two lithologic units on the left side of the prospection.

It is interesting to note that borehole data allowed overcoming ambiguity in the interpretation of the weathered zone geometry. This ambiguity is caused by the lack of

strong continuous markers in the reflection section. Instead, this does not occur in the surface data of VSP 3 and 4. We believe, therefore, that such boundaries can be drawn by correlating the markers detected in VSP 3 and 4 (sector B in Fig. 9).

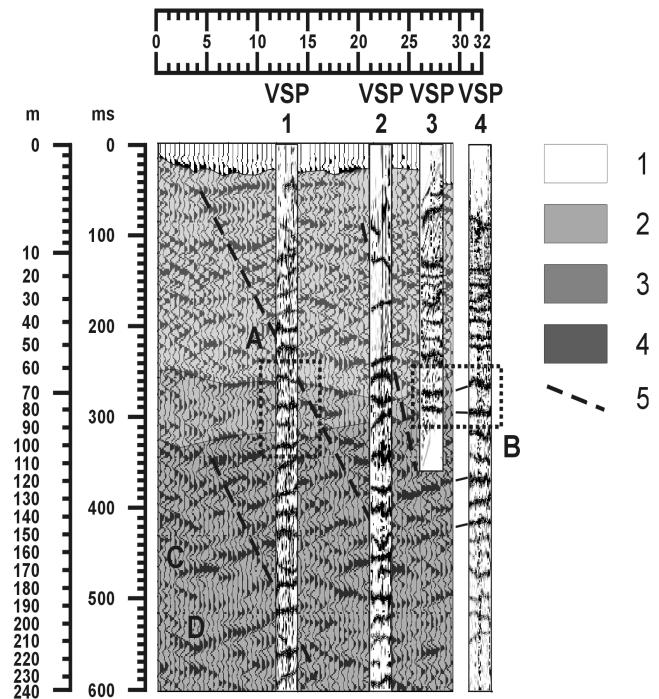


Fig. 9. Superposition of VSP sections over reflection section Ln1 with geological interpretation: 1) alluvial deposits 2) Lacustrine and fluvial deposits 3) Weathered "Macigno" formation 4) "Macigno" formation (middle-upper Oligocene – upper Oligocene) 5) Fractures  
*Sovraposizione delle sezioni VSP sulla sezione di sismica a riflessione Ln1 con interpretazione geologica: 1) Depositi alluvionali 2) Depositi fluvio-lacustri 3) formazione del "Macigno" alterato 4) formazione del "Macigno" (Oligocene medio-superiore – Oligocene superiore) 5) Fratture*

Knowing the depth and the geometry of the seismic bedrock proved to be useful for a 2D numeric model developed with FLAC 4.0 code (Various authors, 1987; Coetzee et al., 1995; Itasca Consulting Group, 2000). The principle phases of the modelling are shown in fig.10.

## 6. Conclusions

The understanding of underground geometries, dynamic properties and thicknesses of lithological entities is of prior importance within the studies of local seismic response as this data is fed as input to numerical modelling code. The present study proves how it is possible to obtain bedrock depth and geometry from down-hole data acquired in geognostic investigation boreholes, that have not reached the bedrock. This has been done with classical down hole SH data that has been properly processed. All down hole

data has been used and not just the first arrivals like normal down hole investigations. The results obtained in the VSP sections have been correlated with borehole stratigraphies

and have been calibrated with high resolution SH reflection seismics.

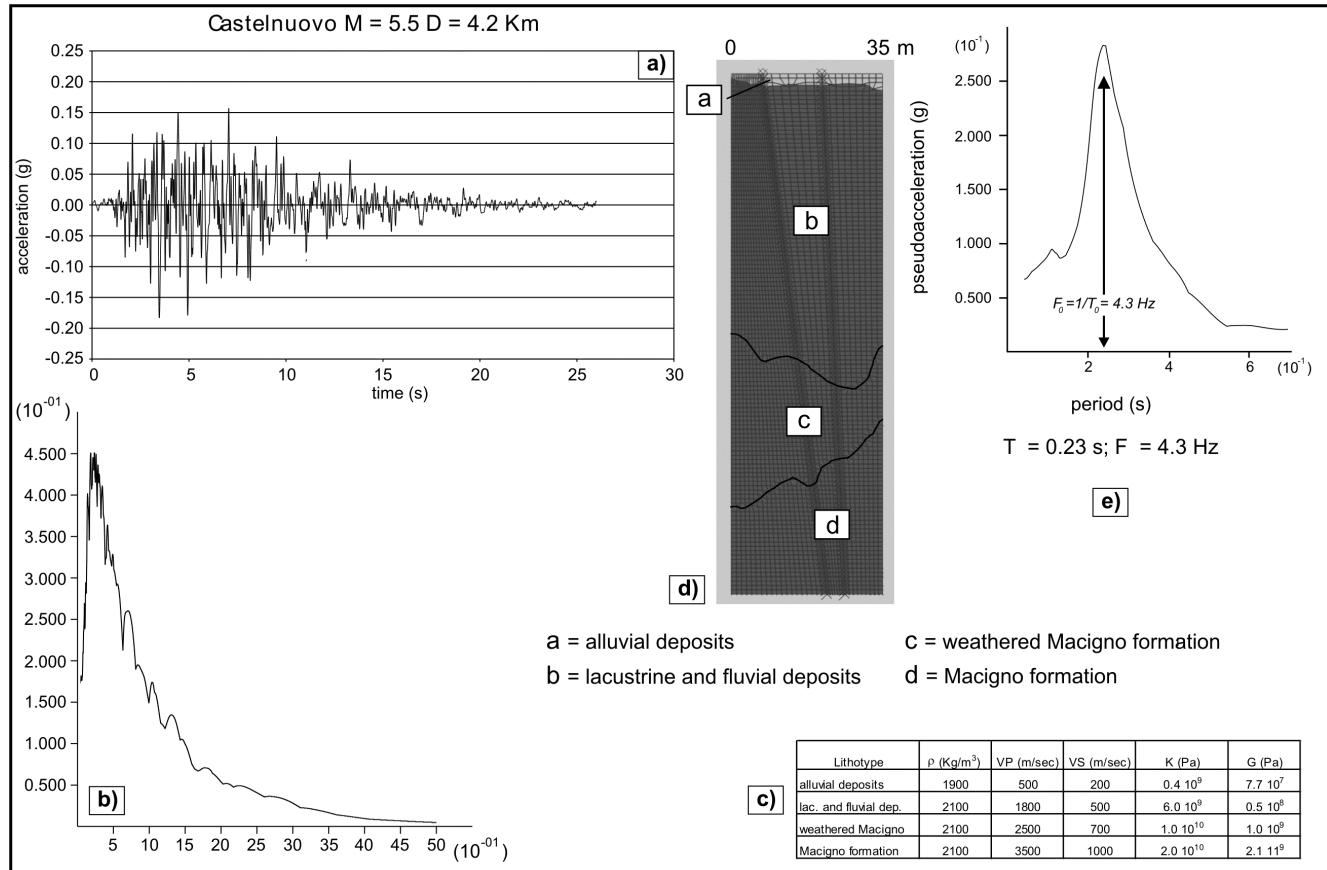


Fig. 10. Input data for the numerical model of the Pieve Fosciana site: a) input motion b) response spectrum; c) used parameters; d) section used in the model; e) results of the numerical model

Dati di input della modellazione nel sito di Pieve Fosciana: a) accelerogramma di riferimento; b) spettro di risposta; c) parametri utilizzati; d) sezione utilizzata nella modellazione; e) risultati della modellazione numerica

Almost all the signals detected in the VSP sections have a clear correspondent with those of the reflection section, both in terms of depth and geometry. Accordingly, the following considerations can be made:

- since a reflection section is characterised by a number of signals, only some of them, generally those more coherent or those corresponding to the conceptual model based on the known data, are considered as real ones. The present work demonstrates, instead, that also those signals generally assumed as noise, have a precise sense: this is supported also by the fact that the disturbances occurring in surface prospection (Love's waves, multiples, diffractions) hardly correspond to those of bore-hole prospection (tube waves, multiple, etc);
- the context of the investigation is characterised by high heterogeneity and anisotropy, and the precise real geometry is not easy to draw, because it is not easy to define the velocity-depth function for the several CDPs; nevertheless,

the two methodologies provided comparable geometries, in spite of different offsets and the low lateral investigation of VSP1;

- the ambiguity experienced in some circumstances in the interpretation of the reflection section has been overcome by using the VSP;
- the geognostic prospection provided a lower resolution of the site anisotropy in respect to that obtained by the geophysics.

VSP investigations have proved to be useful for reconstructing depths and geometry of the underlying bedrock, thus permitting 2D site response analyses.

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