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DOWNHOLE SEISMIC LOGGING FOR DETAILED P-S WAVES VELOCITY DETERMINATION

P.J. KAMBOURIS[1], J.D. ALEXOPOULOS[2], T.D. PAPADOPOULOS[3]

ABSTRACT

Downhole seismic velocity logging has been used in detailed geotechnical surveys for engineering applications. Determination of dynamic elastic constants from acoustic velocity measurements is often a challenging procedure in case of highly variable unconsolidated overburden. Accuracy of P – S cross-hole velocity measurements is greatly enhanced with the methodologies described. Severe ambiguities, primarily in direct shear wave arrivals picking are diminished, as a result of obtaining redundant data sets.

Errors in the determination of zero time inherent to the electronic circuitry or following the use of drill bit or the SPT cone as seismic sources have been decreased by using the standard steel plate and the loaded shear wave plank as alternatives.

Extensive AGC and frequency filtering is applied in order to increase the accuracy of the later arrivals. The picked times, corresponding to the overlapping data sets, are processed according to a method, which finally assigns a velocity value to each depth point.

KEY WORDS: downhole, seismic logging.

1. INTRODUCTION

Although both compressional and shear waves downhole surveys for the determination of unconsolidated overburden dynamic elastic constants are viable geophysical tools, the accuracy in the seismic velocity values calculation seems to be relatively low. Under this restriction the geological structure resolved appears to be crude. This is mainly the result of,

- Single data sets analysis for each depth point
- Use of single borehole geophones
- Unavoidable zero time errors due to electronic circuitry
- High amplitude and frequency noise in places with poor casing bond.
- Tube waves affecting seriously shear waves first break picking

In this paper we will present a method for handling downhole seismic logging, incorporating data acquisition procedures and statistical analysis techniques met in extensive and costly VSP surveys. The examples are drawn from an earthquake hazard assessment project conducted at Olympic 2004 Village area, in a highly variable unconsolidated overburden, without the presence of any distinct geological boundary and we were able to obtain useful velocity–vs–depth results, up to a depth of 50 m.

2. DATA ACQUISITION

Equipment

Data have been recorded using a 24-channel digital IFP engineering seismograph Geometrics STRATAVIEW. The geophone array consisted of eight (8) three-component sensors 5m apart, clamped to the borehole casing, with frequency band between 6-6000 Hz.

Borehole suitability

Special care has been taken in order to achieve the best allowable borehole conditions. The surveyed boreholes have been drilled to the depth of 50 m. They were cased with good quality thin-walled PVC casing and they were

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1. University of Athens, Faculty of Geology, Dpt. of Geophysics & Geothermics, Zografou, 157 84, *pkambouris@geol.uoa.gr*
2. University of Athens, Faculty of Geology, Dpt. of Geophysics & Geothermics, Zografou, 157 84, *jalexopoulos@geol.uoa.gr*
3. University of Athens, Faculty of Geology, Dpt. of Geophysics & Geothermics, Zografou, 157 84, *tpapadop@geol.uoa.gr*

properly grouted with cement, for uniform contact with the surrounding formations. However, perfect grouting seems to be unrealistic and the accuracy in first arrival picking is affected.

Data acquisition techniques

The steel plate and the loaded shear wave plank have been used as the suitable seismic sources. The source offset from the borehole lies typically between 3 and 5 m. This is generally sufficient to minimize interference from the casing wave (traveling along the casing with apparent velocity of approximately 1600-1700 m/s in PVC), yet close enough to avoid coherent noise from refracted waves in near surface layering.

High digital sampling rates (typically 64 μs) are maintained for best resolution in first-break picking.

The geophone array is lowered downhole at an increment of 2.5 m. In every position both steel plate and shear wave plank were used and three successive records (one for P and two for opposite polarity S-waves) acquired. Consequently, overlapping geophone positions result to records with three as the maximum fold of cover (Pullan and MacAulay, 1987). Particularly for S-waves, the fold of cover could be increased to five due to both sides plank strikes. In this way it is possible to obtain a redundancy of data, which may be used to reduce the significance of picking errors. From experience we have found that for boreholes of 50 m or less, sufficient high frequency energy is transmitted from surface to the maximum depth, so the determination of first arrival times may be achieved to an accuracy of less than 1 ms.

Data analysis

The data analysis procedure is based on a modified version of Hunter and Burns "independent" method (Hunter and Burns, 1991). According to that method, each of the 8-channel travel time data set is separately analyzed. After the first arrival picking, the interval velocities are computed across three data point and assigned to the depth location corresponding to the mid-point of the geophone positions being used. Due to the relatively coarse data acquisition interval, we combined two successive data sets for best resolution. With overlapping arrays, more than three independent velocity values could be computed for each depth point (Allison and Shieck, 1996). An exception is inevitable for deeper and shallower depth locations. The redundant velocities are plotted with depth for detecting any abnormal value. The final interval velocity is calculated by computing the weighted average of the independent measurements. The corresponding weights are the inverse least-squares error of the three-point velocity fit (Hunter et al., 1998).

S-waves picking

Shear wave velocity measurements in a borehole require firm coupling of the casing to the formation. Equally important is the ground coupling of the source at the surface, where horizontally energy is produced. Furthermore, picking the onset of shear-wave motion in the presence of source-generated noise (later cycles of P-motion or tube waves) could sometimes be challenging (Figure 1a). The aforementioned drawbacks can be partially overcome using advanced filtering techniques.

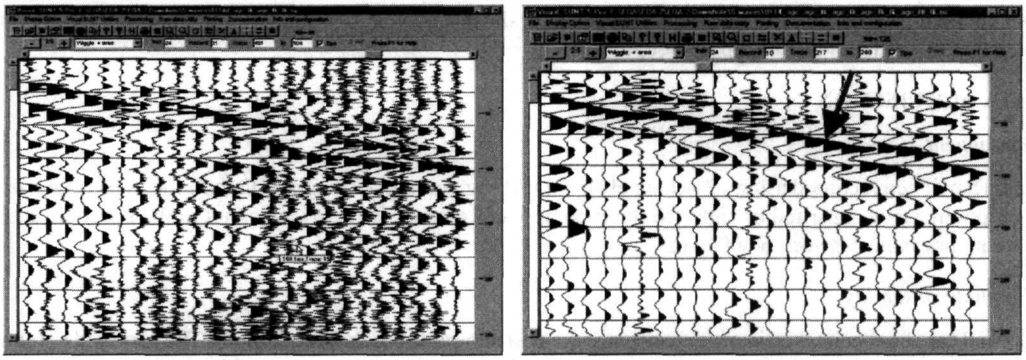


Figure 1a *Figure 1b*

Figure 1: Raw and filtered downhole records.

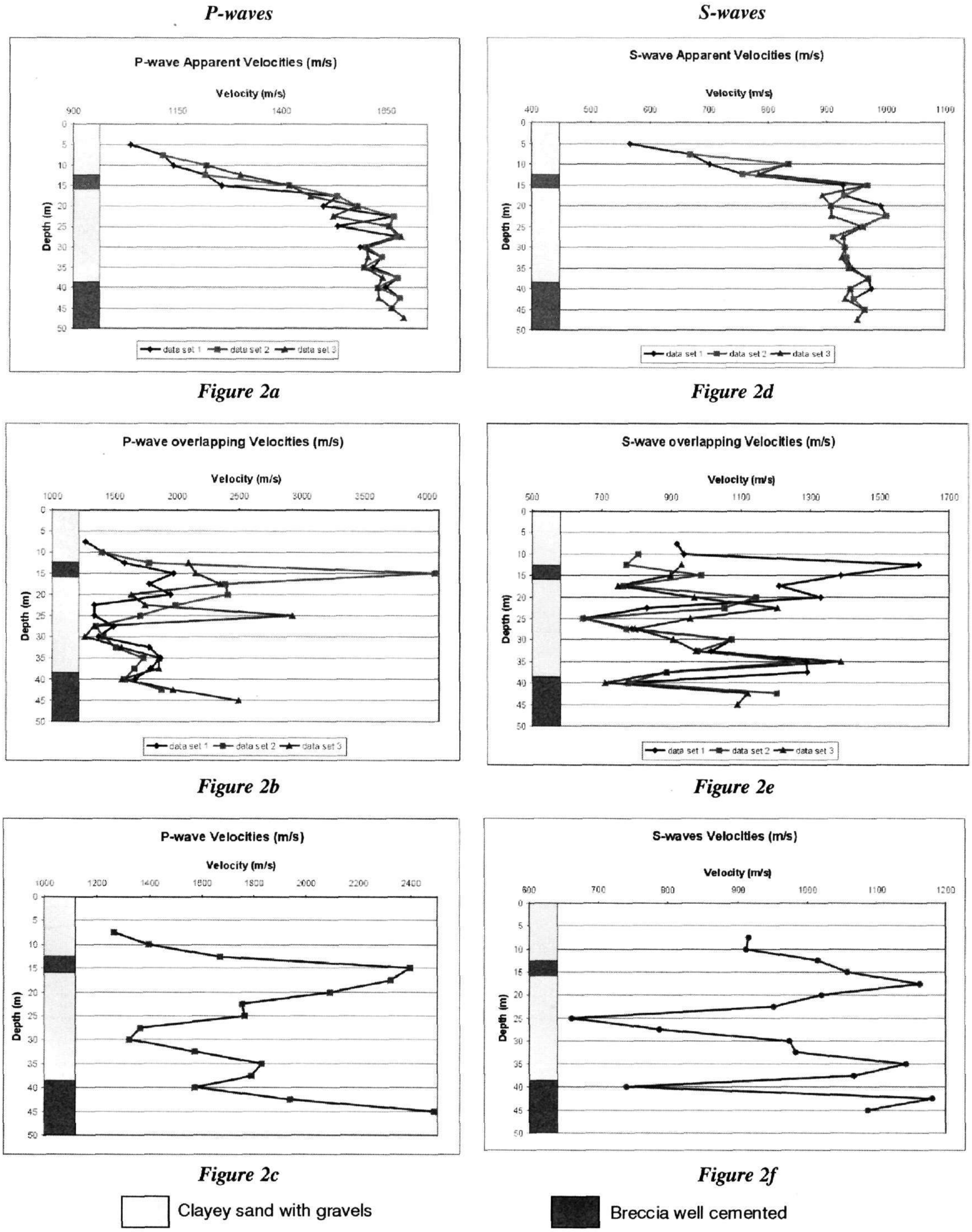


Figure 2a

Figure 2d

Figure 2b

Figure 2e

Figure 2c

Figure 2f

Figure 2: First downhole example processing scheme.

P-waves *S-waves*

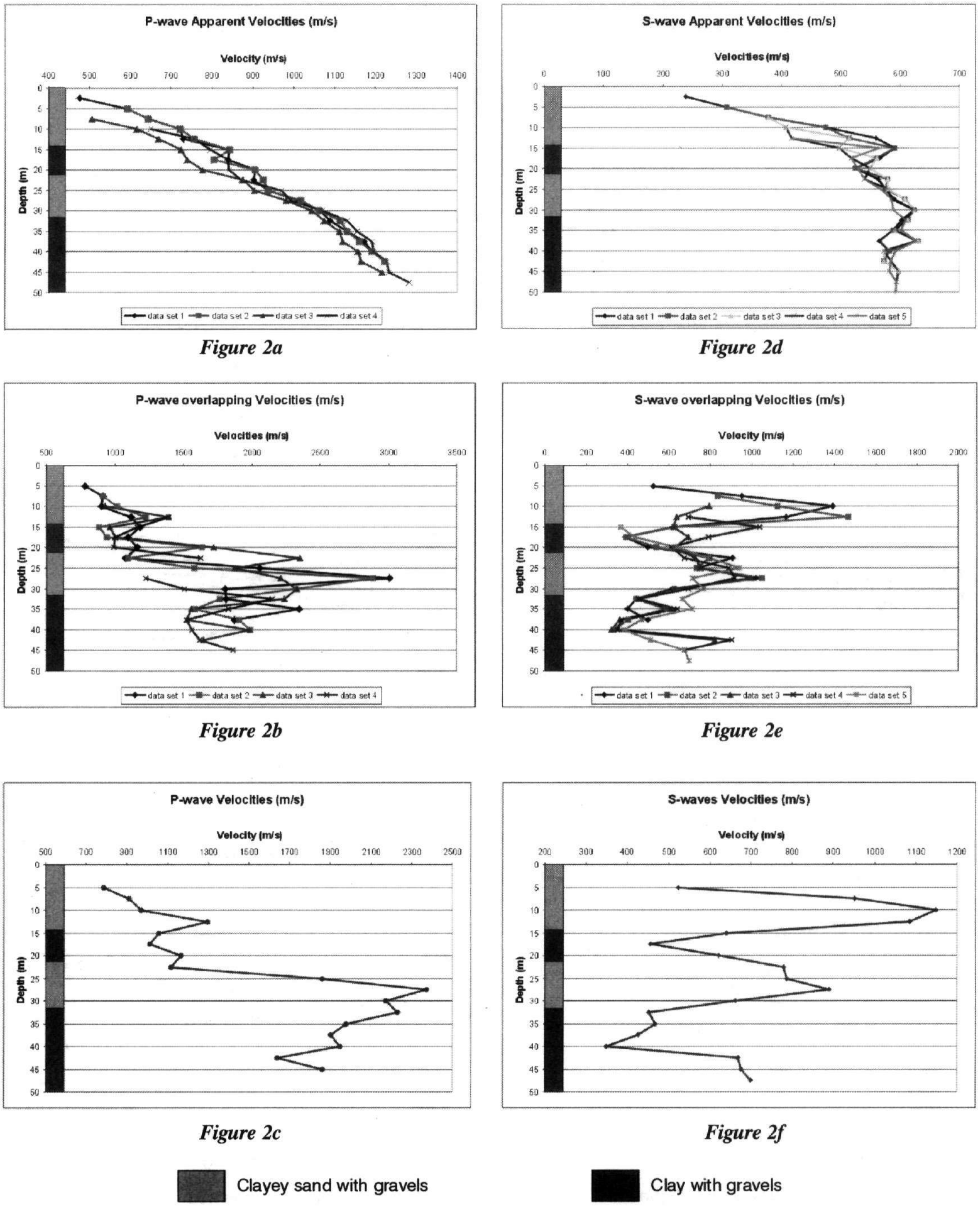


Figure 2a *Figure 2d*

Figure 2b *Figure 2e*

Figure 2c *Figure 2f*

Figure 3: Second downhole example processing scheme.

The filtered record suite (Figure 1b) was created by using a long automatic gain control (AGC) window, which somewhat suppresses the first arrival, hence the P-wave energy, but also increases the relative amplitude of ambient noise. Successive frequency filtering application, after an extensive Fourier analysis, could suppress adequately the unwanted noise, without modification of the source wavelet. The red arrow (Figure 1b) displays the picked S-wave first break.

3. EXAMPLES

Both examples are drawn from an earthquake hazard assessment project in the same geological environment.

First downhole logging example

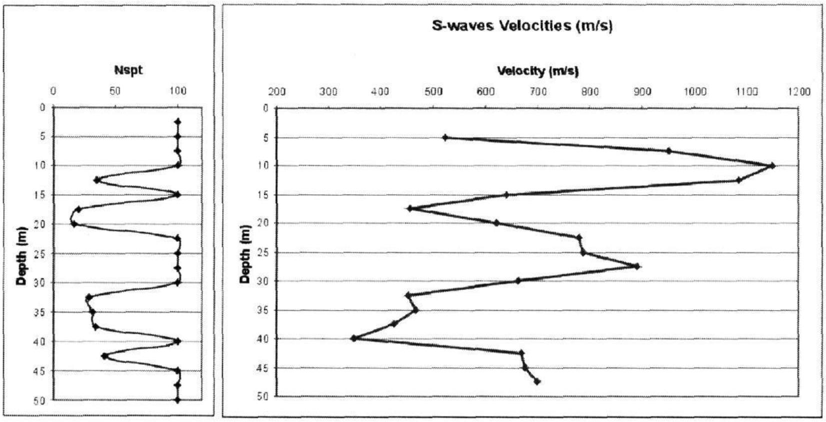
According to borehole drilling data, the general geology of the surveyed area consists of alternations of unconsolidated silts, clays and sands mainly with gravels. The only well cemented formation appears to be the breccia.

The first major velocity discontinuity is located better at S-waves than P-waves apparent velocities graphs (Figures 2a, 2d). This kind of diagrams intent to reveal any abrupt changes in velocity values and are very useful in this example. The small differences on the apparent velocity distributions show only minor disagreements in picked times for various data sets. The same result comes up from the overlapping velocities graphs shown in (Figures 2b, 2e), which are the products of the three-point least squares fit, for each couple of the data sets. The minor velocity values deviation shown at "data set 1" (Figure 2e) is effectively adjusted through the statistical procedure. The final velocity distribution is in good correlation with the geological data (Figures 2c, 2f). The major velocity peaks at about 25 and 40m respectively, could be associated with the presence of the overconsolidated breccia. The intermediate significant velocity reduction may also be attributed to the thick clayey sand formation.

Second Downhole example

In this example the P-wave Apparent velocities graph (Figure 3a), contrary to S-wave one (Figure 3d), provides no evidence of velocity changes with depth. A continue P-wave velocity increase is displayed up to the depth of 27.5 m (Figure 3b).

The alternations of sands and clays are noticeable at P and S overlapping velocities graphs (Figures 3b, 3e), as well as at the final velocity plots (Figures 3c, 3f). In relation with laboratory lithological analysis, the velocity maxima are obvious at portions of the borehole, where the main formation substance is sand with gravels (more than 65%). The lower velocity values could be associated with clays and silts (more than 65 %). Moreover, the velocity variation is far more distinctive for S-waves rather than for P-waves (Figures 3c, 3f). The results may be enhanced if we take into account the Nspt measurements (Figure 4). The above comparison becomes very important in cases of earthquake applications from engineering point of view.



**** Nspt value 100 is representative of refusal***

Figure 4: Nspt and S-wave velocity comparison

4. CONCLUSION

Experience acquired with the eight, three-component geophone chain has shown, that it can yield accurate P and S-wave interval velocities in unconsolidated overburden. The multichannel capacity is required to compensate for uncertainties in time zero between successive shots. The ability to obtain accurate velocities is also developed by statistically analyzing redundancy of downhole data. The modified "independent" technique provides with a better velocity control even for unlithified materials. Meticulous frequency analysis could improve the accuracy in S-waves first-break picking, without any loss of information.

The implementation of cross-hole technique has become a standard in engineering problems. However, many questions can only be answered definitely with results from a downhole seismic logging survey. The cost effectiveness of such kind of study cannot be denied particularly in "demanding" geological environment. The analysis procedure is relatively simple and may be accomplished easily using straightforward calculations.

It is hoped that the techniques and examples given here have shown that downhole seismic logging should be a substantial part of any geotechnical investigation whenever possible.

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