COMPARISON OF SHEAR-WAVE VELOCITY-DEPTH PROFILES FROM DOWNHOLE AND SURFACE SEISMIC EXPERIMENTS

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ABSTRACT

We conducted shallow seismic survey at 10 strong-motion stations in Turkey and estimated shear-wave velocities down to a depth of 30 m using the method of multichannel analysis of surface waves (MASW). At each station site, we also drilled a borehole with casing down to 30-m depth and determined a downhole shear-wave velocity-depth profile. We then compared the shear-wave velocity-depth profiles estimated by the MASW and determined by the downhole seismic survey. We also had the opportunity to compare both sets of profiles with the estimates from the spectral analysis of surface waves (SASW) previously reported. An integrated data acquisition system that includes an accelerated impact source with a 50-kg weight, a 48-channel receiver cable with 2-m geophone interval and 4.5-Hz vertical geophones, and two 24-channel, 24-bit Geode recording units was used to acquire the shallow seismic data. We acquired two 48-channel seismic records at each of the station sites using the common-spread recording geometry. By applying Rayleigh-wave inversion to the surface waves isolated from the shot records, we estimated an S-wave velocity-depth profile for the site. For the downhole seismic survey, we used a three-component 14-Hz borehole geophone and a shear-wave impact source at the surface, and recorded data at 1-m depth intervals. We find that there exists a 10-15% difference between the velocities determined by the surface-wave and downhole seismic methods --- consistent with the previously reported results. The surface-wave method yields a spatially averaged velocity-depth profile along the line traverse coincident with the geophone spread, whereas the downhole seismic method yields a velocity-depth profile that is pertinent to the borehole location, only. As such, the downhole measurements can be adversely affected by the local borehole conditions. We believe that the spatially averaged velocities estimated by the surface-wave methods may be more desirable for site-specific characterization to determine geotechnical earthquake engineering parameters.

KEYWORDS: Rayleigh-wave inversion, MASW, SASW, borehole seismic

1. INTRODUCTION

As part of a research project directed by the Department of Civil Engineering, Middle East Technical University, Ankara, Turkey, on “Compilation of Data Base for the National Strong-Motion Seismograph Network” we performed geotechnical drilling and conducted borehole seismic surveys at nine of the national grid for strong-motion station sites to determine S-wave velocities down to a depth of 30 m. We compared the borehole S-wave velocity estimates with the velocities estimated by the surface seismic MASW (Multichannel Analysis of Surface Waves) method reported by Yilmaz et al. (2008) in this volume. The nine station sites for borehole seismic survey were selected based on one or more of the following criteria: (a) recordings from large earthquakes, (b) soil column composed of alluvials, and (c) lateral and vertical heterogeneity within the soil column.

Based on experience, borehole seismic surveys give most reliable results in alluvial soils. In contrast, good quality records may not be acquired from borehole seismic surveys in case of rocks with large fractures, causing poor transmission of wave motion from the surrounding medium to the PVC casing then to the borehole geophone. Finally, at some station sites, as a result of accumulated mud at the well bottom, the maximum depth for the borehole seismic survey is less than 30 m.

2. SEISMIC DATA ACQUISITION

An integrated system that includes the source, cable and geophones, and recording unit has been designed for the seismic field work. The system components are listed in Table 1 and the data acquisition parameters are listed in Table 2.

Table 1. Components of the seismic recording system.

1	9-kg hand-held hammer and a plank with 240-cm in length and 20-cm in diameter flattened at the top and bottom surface in contact with the ground surface.
2	a 14-Hz downhole geophone with three components (*X,Y,Z*: longitudinal, transversal, vertical) the geophone compass, and a 1-m probe that houses the geophone and the compass, which is lowered downhole with a cable that is connected to the geophone control unit.
3	Geostuff geophone control unit and Geode recording unit

Table 2. Recording parameters for the seismic survey.

Borehole geophone type	14 Hz, *(X,Y,Z)* three-component
Number of records at each depth level	3
Number of channels per record	3
First channel	*Z* component
Second channel	*X* component
Third channel	*Y* component
Min-max depth of recording	1-30 m
Depth interval for recording	1 m
Number of records at each station site	90
Number of traces at each station site	270
Sampling rate	0.125 ms
Trace length	500 ms
Recording format	SEG2

At each station site, three records each with three channels were acquired at 1-m depth interval within a depth range of 1-30 m inside a borehole with PVC casing and backfilled with pea gravel or sand in order for the wave motion to be transferred from the soil column to the geophone. The SEG2 format, which is standard in engineering seismology, was used to record the data. The field work using the integrated system described in Table 1 was carried out as follows:

(1) The geophone probe was rotated such that the *X*-component of the geophone is oriented parallel to the plank used as a seismic source and placed 1-m away from the well head.
(2) Then, the geophone probe was lowered to the maximum depth of recording (30 m) using the cable connected to the geophone control unit and tension was applied to the clamp so as to achieve a firm contact with the borehole perimeter.
(3) The signal was transmitted via the geophone cable to the Geostuff geophone control unit. The (*Z,X,Y:* vertical, longitudinal, transversal) components defined by the control unit and each recorded on one channel (*Z*: first channel, *X:* second channel, and *Y:* third channel) were then transmitted to the Geode recording unit, and were converted from analog to digital form. Subsequently, this three-channel digital signal was transmitted to the laptop from the recording unit.

(4) The following records were acquired in the order listed below:
First record: A P wave was generated by a *vertical impact* using a hand-held hammer applied onto an aluminum plate placed 1-m away from the well head and the (*Z,X,Y*) components were each recorded on three channels. Only the first channel of this record that records the *Z* component subsequently was used during the analysis. *Second record:* An S wave whose direction coincides with the direction of the *X* component was generated by a *horizontal impact* using the hand-held hammer applied to one end of a plank, placed 1-m away from the well head, and the (*Z,X,Y*) components were each recorded on three channels. Only the second channel of this record that records the *X* component subsequently was used during the analysis. *Third record:* Another S wave whose direction coincides with the direction of the *X* component was generated by a *horizontal impact* using the hand-held hammer applied to one end of the plank in the *opposite direction* as for the second record, and the (*Z,X,Y*) components were each recorded on three channels. Again, only the second channel of this record that records the *X* component subsequently was used during the analysis.

(5) The tension applied to the clamp on the geophone probe was slightly released and the probe was pulled by 1 m up to the next depth level, then tension again was applied to the clamp so as to achieve a firm contact with the borehole perimeter. At this new depth level, the compass preserves the orientation of the *X*-component of the geophone parallel to the plank. The recording was continued in the manner described above.

At each station site, three records each with three channels recorded between the depth range 1-30 m at 1-m interval were then sorted to obtain three records, each with 30 channels, for P, S+, ve S- waves (Figure 1). S+ and S- records contain signals obtained by a *horizontal impact* source applied in opposite directions. Ideally, the first-arrival wavelets on the S+ and S- records should be identical but with reverse polarity, and the arrival times should also be identical. Nevertheless, ideal conditions for recording are not always possible resulting from an incomplete backfill behind the casing or a collapse around the well periphery giving rise to cavities, or in the presence of rock with fractures. A such, by picking both the S+ and S- first-arrival times, not only the accuracy of the traveltimes but also the S-wave velocities derived from them are verified.

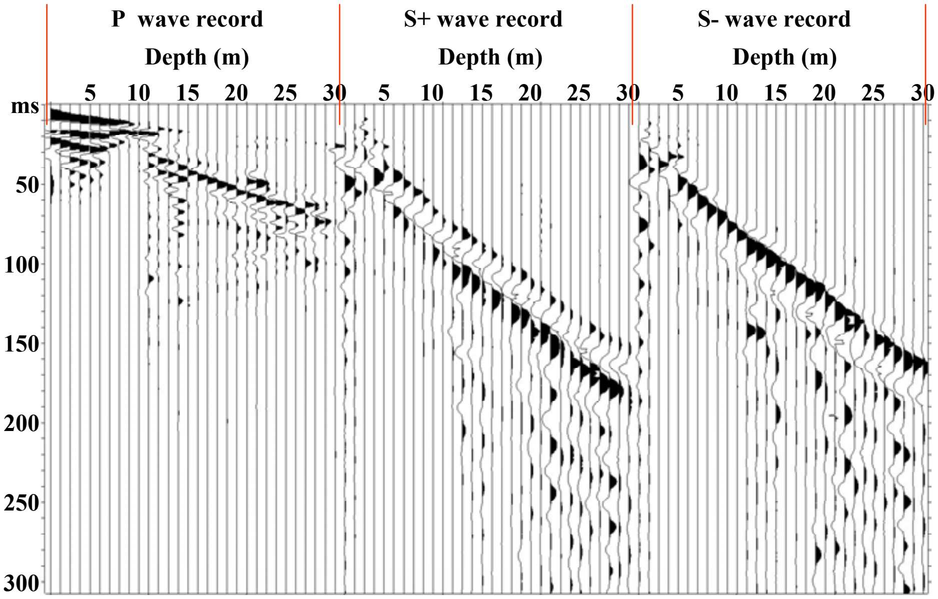

Figure 1. Example P, S+, ve S- borehole seismic records acquired by the borehole survey at station site AI_137_DIN. Three records each with three channels were recorded between the depth range 1-30 m at 1-m interval, which were then sorted to obtain these three records, each with 30 channels, for P, S+, ve S- waves.

3. SEISMIC DATA ANALYSIS

P and S first-arrival times were picked from the three records (Figure 1) created by sorting the data acquired at each station site associated with P, S+, and S- waves. Next, using the angle between the borehole axis and the direction along the surface source-borehole receiver pair, a '*cosine'* correction was applied to the picked times to account for the 1-m distance from the seismic source at the surface to the well head (Figure 2). This correction means as though the data were recorded with the seismic source placed exactly at the well head. Finally, S-wave velocities were determined (Figure 3) from the *dt/dz* changes on the corrected traveltime curves (Figure 2).

Ideally, for each depth, the first-arrival wavelets on the S+ and S- records should be identical but with reverse polarity, and the arrival times should also be identical. Unfortunately, such desirable recording conditions may not always be achieved. Therefore, by picking both the S+ and S- first-arrival times, not only are the accuracy of the traveltimes but also the S-wave velocities derived from them verified. The closer the S+ and S- arrival times are, the more accurate are the determination of the *dt/dz* changes (Figure 2), and therefore the more accurate are the calculated velocities (Figure 3). For each station site, the borehole seismic (BHS) velocity-depth values are given in Table 3.

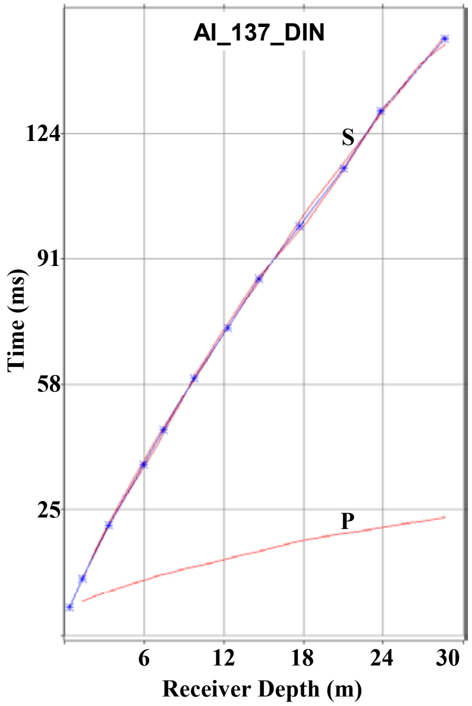

Figure 2. P and S wave arrival times (red curves) at station site AI_137_DIN after the *cosine* correction has been applied. There are two traveltime curves for the S wave picked from the S+ and S- records shown in Figure 2. By determining the *dt/dz* changes on the corrected traveltime curves (blue asterisks), an S-wave velocity-depth profile was obtained for the site (Figure 3).

4. COMPARISON OF SURFACE SEISMIC AND BOREHOLE SEISMIC VELOCITY ESTIMATES

The comparison of the borehole seismic velocity-depth profiles with those of the surface seismic method (MASW --- Multichannel Analysis of Surface Waves, Xia et al. (1999)) reported by Yilmaz et al. (2008) in this volume, and, if available, with those of the surface seismic method (SASW --- Spectral Analysis of Surface Waves, Stokoe et al. (1994)) reported by Rathje et al. (2002) and Rathje et al. (2003) is shown in

Figure 3. For each station site, the borehole seismic (BHS) and the surface seismic (MASW and SASW) velocity-depth values are given as in Tables 3a,b.

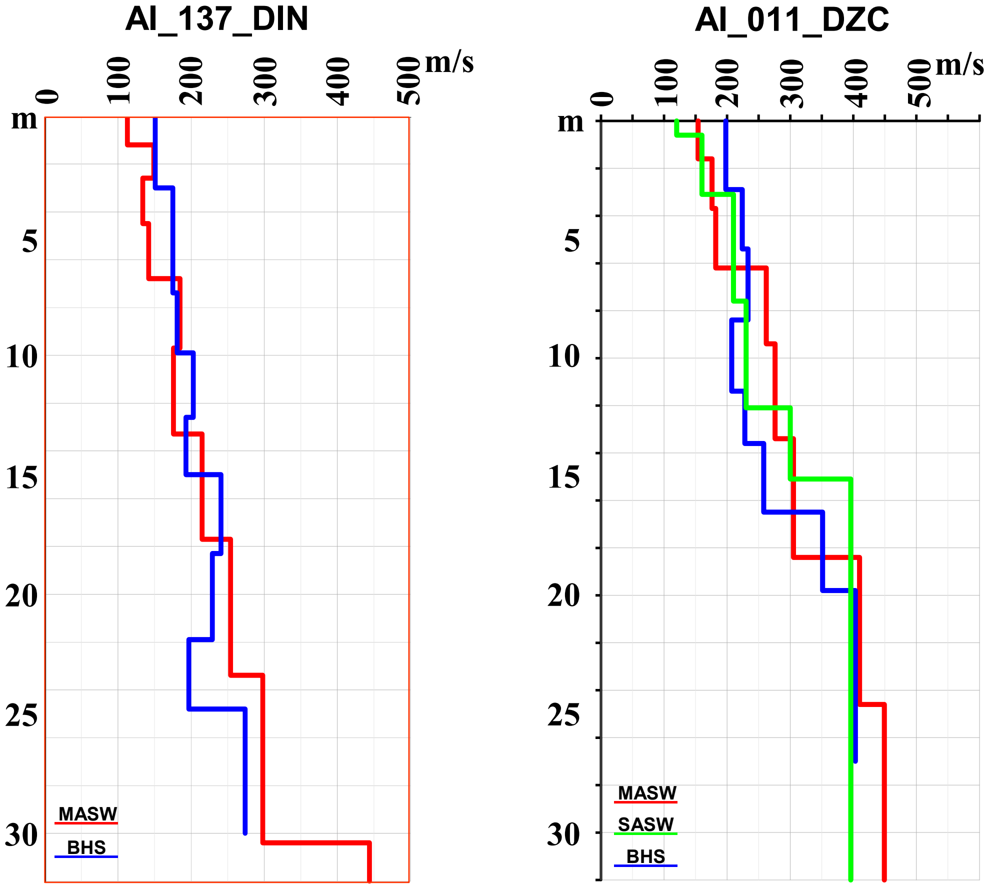

Figure 3. The comparison of the S-wave velocity-depth profile at station sites AI_137_DIN and AI_011_DZC derived from the BHS borehole seismic survey with the results of the surface-seismic methods MASW (Yilmaz et al., 2008) and SASW (Rathje et al., 2002; Rathje et al., 2003). Numerical values are listed in Tables 3a,b.

Table 3a. Velocity-depth profile values from borehole seismic (BHS) and surface seismic (MASW surveys at station site AI_137_DIN.

Depth Interval (m)	*BHS V_s (m/s)*	*Depth Interval (m)*	*MASW V_s (m/s)*
0-3	151	0-1.2	113
3-5.8	175	1.2-2.6	149
5.8-7.4	175	2.6-4.5	134
7.4-9.9	181	4.5-6.8	142
9.9-12.6	203	6.8-9.7	185
12.6-15	193	9.7-13.3	176
15-18.3	241	13.3-17.7	215
18.3-21.9	229	17.7-23.4	254
21.9-24.8	197	23.4-30.4	298
24.8-30	274	30.4-32	444

Table 3b. Velocity-depth profile values from borehole seismic (BHS) and surface seismic (MASW and SASW) surveys at station site AI_011_DZC.

Depth Interval (m)	*BHS V_s (m/s)*	*Depth Interval (m)*	*MASW V_s (m/s)*	*Depth Interval (m)*	*SASW V_s (m/s)*
0-2.9	198	0-1.6	154	0.0-0.6	120
2.9-5.4	224	1.6-3.7	176	0.6-3.1	160
5.4-8.4	233	3.7-6.2	182	3.1-7.6	210
8.4-11.4	207	6.2-9.4	262	7.6-12.1	230
11.4-13.6	228	9.4-13.4	276	12.1-15.1	300
13.6-16.5	258	13.4-18.4	305	15.1-43.1	400
16.5-19.8	351	18.4-24.6	407		
19.8-27	401	24.6-32	449		

The percent difference between the depth-averaged borehole seismic and surface seismic velocities for each station site is given as in Table 4. Finally, average *Vs_avg* values derived from the velocities given by Tables 3a,b for borehole seismic and surface seismic surveys are given in Tables 5a,b,c. The following conclusions were reached from the comparison of the borehole seismic and surface seismic velocities:

(1) For soil profiles composed of primarily alluvial deposits, especially with lateral homogeneity, differences between the borehole seismic and surface seismic velocities are less than 15% as shown in Table 4. This conclusion is consistent with the results obtained by Xia et al. (2000) from seismic investigation of the alluvial deposits in Canada, where differences as much as 15% have been observed between the borehole seismic (BHS) and surface seismic (MASW) velocities. In a survey conducted in the Ilan Province of Taiwan, Kuo et al. (2008) have reported similar amount of depth-dependent differences, even higher percentages in some cases, between the velocities derived from PS logging (a method based on downhole source and receiver) and SWPM method (a surface seismic method based on the SASW method with regards to the data analysis).

(2) The differences between the borehole seismic and surface seismic velocities do not exhibit a systematic behavior. Specifically, depending on the depth, velocities from one method may be more or less than those from the other method. The same conclusion also has been reached by Xia et al. (2000).

(3) When the soil column has lateral heterogeneity, the likelihood of more than 15% difference between the borehole seismic and surface seismic velocities increases (Table 4).

(4) At station site AI_005_SKR, the 26% difference (Table 4) between the surface seismic and borehole seismic velocities may be attributed to the fact that the soil column is composed of limestone, rather than alluvium. Within a soil column with limestone, the likely presence of cavities around the borehole could give rise to relatively lower borehole seismic velocities.

(5) At station site AI_081_IZN_KY, the 24% difference between the borehole seismic and surface seismic velocities (Table 4), despite the alluvial soil column, may be attributed to the poor recording conditions resulting from excessive collapse around the periphery of the borehole.

(6) In general, we observe that differences in borehole seismic and surface seismic velocities are within 15% range in alluvial soil columns with lateral homogeneity. In contrast, within non-alluvial soil columns with some lateral heterogeneity, differences in borehole seismic and surface seismic velocities may be more than 15%. Additionally, in cases of difficult borehole conditions --- the incomplete backfill with pea gravel or sand, cavities formed by collapse around the periphery, or fractures within a rock column, may cause poor quality in borehole seismic recording.

Table 4. The depth average of percent differences between the borehole seismic (BHS) and surface seismic (MASW) velocities given in Table 5. The values above the %15 threshold are indicated in red. The percent averages in this table are based on the BHS maximum depth values.

Station	*% Difference*
AI_004_IZT_2	2
AI_004_IZT_3	32
AI_005_SKR	26
AI_007_GYN_BHM	55
AI_010_BOL	-10
AI_011_DZC	-3
AI_081_IZN_KY	-24
AI_088_CNK	-2
AI_115_BRN_BAY	-13
AI_137_DIN	1

Table 5a. The *Vs_avg* values derived from the velocities and thicknesses given by Table 4 for borehole seismic (BHS) and surface seismic (MASW and SASW) surveys. For each survey (BHS, MASW, and SASW), the average velocities correspond to the depth intervals indicated in parentheses. The average velocities were calculated using the NEHRP time-average formula (BSSC, 2004) by taking the ratio of the sum of the ratio of the layer thickness to the layer velocity given by Table 4 to the total thickness.

Station	*BHS Vs_avg*	*MASW Vs_avg*	*SASW Vs_avg*
AI_004_IZT_2	744 (0 - 20 m)	827 (0 - 30 m)	578 (0 - 16 m)
AI_004_IZT_3	928 (0 - 16 m)	827 (0 - 30 m)	578 (0 - 16 m)
AI_005_SKR	526 (0 - 30 m)	412 (0 - 30 m)	430 (0 - 25 m)
AI_007_GYN_BHM	1056 (0 - 30 m)	471 (0 - 30 m)	
AI_010_BOL	266 (0 - 28 m)	294 (0 - 30 m)	288 (0 - 30 m)
AI_011_DZC	266 (0 - 27 m)	282 (0 - 30 m)	276 (0 - 30 m)
AI_081_IZN_KY	167 (0 - 30 m)	197 (0 - 30 m)	189 (0 - 15 m)
AI_088_CNK	187 (0 - 29 m)	192 (0 - 30 m)	
AI_115_BRN_BAY	175 (0 - 30 m)	195 (0 - 30 m)	
AI_137_DIN	203 (0 - 30 m)	198 (0 - 30 m)	

Table 5b. The *Vs_avg* values derived from the velocities and thicknesses given by Table 4 for borehole seismic (BHS) and surface seismic (MASW) surveys. The average velocities correspond to the depth intervals indicated in parentheses. The average velocities were calculated using the NEHRP time-average formula (BSSC, 2004) by taking the ratio of the sum of the ratio of the layer thickness to the layer velocity given by Table 4 to the total thickness. Percent differences were calculated using the formula *100* x *(BHS-MASW) / BHS*. The values above the %15 threshold are indicated in red.

Station	*BHS Vs_avg*	*MASW Vs_avg*	*%Difference*
AI_004_IZT_2	744 (0 - 20 m)	683 (0 - 20 m)	8
AI_004_IZT_3	928 (0 - 16 m)	622 (0 - 16 m)	33
AI_005_SKR	526 (0 - 30 m)	412 (0 - 30 m)	22
AI_007_GYN_BHM	1056 (0 - 30 m)	471 (0 - 30 m)	55
AI_010_BOL	266 (0 - 28 m)	285 (0 - 28 m)	-7
AI_011_DZC	266 (0 - 27 m)	271 (0 - 27 m)	-2
AI_081_IZN_KY	167 (0 - 30 m)	197 (0 - 30 m)	-18
AI_088_CNK	187 (0 - 29 m)	189 (0 - 29 m)	-1
AI_115_BRN_BAY	175 (0 - 30 m)	195 (0 - 30 m)	-11
AI_137_DIN	203 (0 - 30 m)	198 (0 - 30 m)	2

Table 5c. The *Vs_avg* values derived from the velocities and thicknesses given by Table 4 for surface seismic SASW and MASW surveys. The average velocities correspond to the depth intervals indicated in parentheses. The average velocities were calculated using the NEHRP time-average formula (BSSC, 2004) by taking the ratio of the the sum of the ratio of the layer thickness to the layer velocity given by Table 4 to the total thickness. Percent differences were calculated using the formula *100* x *(SASW-MASW) / SASW*.

Station	*SASW Vs_avg*	*MASW Vs_avg*	*%Difference*
AI_004_IZT_2	578 (0 - 16 m)	622 (0 - 16 m)	-8
AI_004_IZT_3	578 (0 - 16 m)	622 (0 - 16 m)	-8
AI_005_SKR	430 (0 - 25 m)	379 (0 - 25 m)	12
AI_007_GYN_BHM		471 (0 - 30 m)	
AI_010_BOL	288 (0 - 30 m)	294 (0 - 30 m)	-2
AI_011_DZC	276 (0 - 30 m)	282 (0 - 30 m)	-2
AI_081_IZN_KY	189 (0 - 15 m)	161 (0 - 15 m)	15
AI_088_CNK		192 (0 - 30 m)	
AI_115_BRN_BAY		195 (0 - 30 m)	
AI_137_DIN		198 (0 - 30 m)	

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