AN INTEGRATED SHALLOW SEISMIC SURVEY FOR GEOTECHNICAL MODELING - A CASE STUDY

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ABSTRACT: The city of Istanbul and its environs constitute the economic heartland of Turkey. It has grown at an exceptionally rapid pace in recent years. This has caused a construction boom of high-rise residential and office buildings. As such, geotechnical and geodynamic subsoil modeling is imperative for foundation engineering assessment of a high-rise structure site. Additionally, design of high-rise structures requires computing site-specific response spectra for future earthquakes. The subsoil formation in Istanbul is of claystone, siltstone, and sandstone, with or without alterations and structural discontinuities. To create parking space, deep excavations are undertaken to accommodate multi-storey basements beneath tower structures. It is not uncommon to have excavations to depths 25-40 m below the ground level. As a result, it is compulsory for geotechnical engineers to derive geotechnical model of the subsoil well below the foundations. This in turn requires seismic investigations with target depths greater than 50 m below the ground level. A case study for an integrated shallow seismic survey at the future site of a tower structure is presented with a foundation depth of 40 m below the ground level. Inversion of refracted-wave arrival times to estimate the P-wave velocity-depth model of the soil and subsoil column, and inversion of Rayleigh-type surface waves to estimate the S-wave velocity-depth model of the soil column are performed.
Keywords: Seismic survey, integrated approach, geotechnical modeling, case study

1. INTRODUCTION

An integrated shallow seismic survey is conducted for geotechnical characterization of the future site of a residential and office tower in Istanbul. 48-channel seismic records along five line traverses using common-spread recording geometry with 4-m shot interval and 4-m geophone interval are acquired. The P-wave velocity-depth models along the line traverses are estimated by nonlinear inversion of the first-arrival times picked from the recorded shot gathers. The geometry of the layers within the near-surface and that of the near-surface-bedrock interface are delineated based on P-wave velocity variations along the line traverses. Additionally, by using a receiver spread with 48 geophones at 2-m intervals, three shot records; two at the end and one at the center of the spread at six locations within the site are required. The S-wave velocity-depth profiles are estimated by inversion of Rayleigh-type surface waves observed on the recorded shot records.

The near-surface at the site comprises three main units starting from the ground level: (1) top soil and/or fill with velocities varying between 500-1,000 m/s and thickness varying between 3-18 m; (2) heterogeneous layer with velocities varying between 1,000-2,500 m/s and thickness varying between 10-35 m; (3) homogeneous layer with velocities varying between 2,500-3,500 m/s, mostly in the vertical direction, and thickness varying between 10-20 m. Below the near-surface layers is the geological bedrock with velocities exceeding 3,500 m/s. P-wave velocities generally are 10-20% higher in the NS direction than the velocities in the EW direction, particularly within the third layer and the bedrock. Such directional difference in velocities may be attributed to seismic anisotropy caused by fracture planes in the EW direction that may be present in the third layer and the bedrock. The depth of the near-surface-bedrock interface varies between 20-45 m. The interfaces between the near-surface units and the near-surface-bedrock interface have a prominent three-dimensional character. Some dikes and faults can also be inferred from the structural interpretation of the P-wave velocity-depth models based on velocity contrast. The maximum depth at which the S-wave velocity reaches 700 m/s value can be considered as the soil-geotechnical bedrock interface. The depth of this soil-bedrock interface at the site varies between 6-22 m from the ground level.

2. DATA ACQUISITION

The seismic survey is in two parts; refraction profiling along the specified line traverses and surface-wave profiling centered at specified locations within the survey area as shown in Figure 1. Along the line traverses, topographic variations are no more than 3 m; hence, analysis of the data was based on the flat-datum assumption.

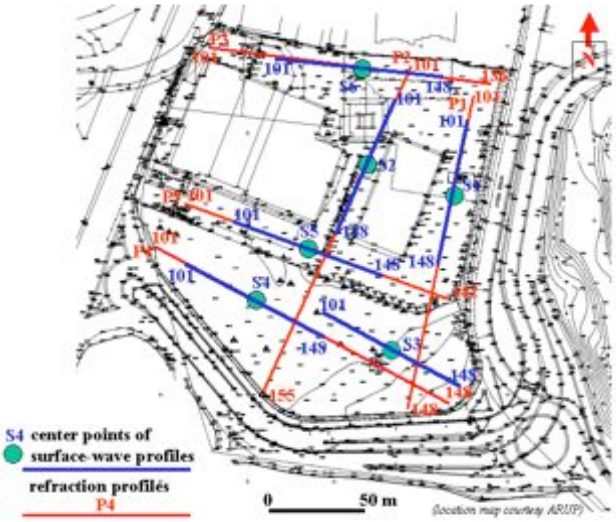

Figure 1. Location map of the site of investigation. The site is about 8 acres in size. The red lines P1-P5 represent the receiver spreads refraction profiles and the green circles S1-S6 correspond to the center of the receiver spreads represented by the blue lines for Rayleigh-wave inversion to estimate the shear-wave velocity-depth profiles. The numbers annotated on the lines represent the first and last shot/receiver stations. Map scale is approximate.

Refraction Profiling. Along the line traverses P1-P5 as shown in Figure 1, seismic data is recorded using a 50-kg accelerated impact source, and a common-receiver spread geometry with 48 4.5-Hz vertical geophones at 4-m intervals. Specifically, while keeping the receiver spread fixed, common-shot gathers at shot locations from one end of the line traverse to the other at 4-m intervals, are recorded.

Surface-Wave Profiling. By using a receiver spread centered at locations S1-S6 as indicated in Figure 1, seismic data is recorded using a receiver spread with 48 4.5-Hz geophones at 2-m intervals. Specifically, while keeping the receiver spread fixed, three common-shot gathers; two at each end and one at the center of the spread are recorded.

3. DATA ANALYSIS

Table 1 shows the workflow for the analysis of refracted waves on the records obtained from the refraction profiles P1-P5 (Yilmaz and Eser, 2002). The objective is to estimate the P-wave velocities down to a depth greater than 50 m along the line traverses within the soil column and the underlying bedrock. Figure 2a shows the first-arrival times picked from the shot gathers along Line P1 used in nonlinear traveltime tomography (Zhang and Toksoz, 1998) to estimate the P-wave velocity-depth model as shown in Figure 2b.

Table 1. Workflow for analysis of refracted waves.

1	Pick the traveltimes associated with the first arrivals.
2	Construct an'initial' model for the near-surface that is defined by a set of horizontal layers each with constant P-wave velocity.
3	Compute the refracted traveltimes associated with the initial model.
4	Perturb the initial model parameters until the difference between the modeled and the observed traveltimes is minimum in the least-squres sense, and create a 'final' model of the P-wave velocity field for the near-surface. The model perturbation is based on nonlinear traveltime tomography, which acoounts for not only the traveltimes but also the traveltime gradients so as to resolve lateral as well as vertical velocity variations.

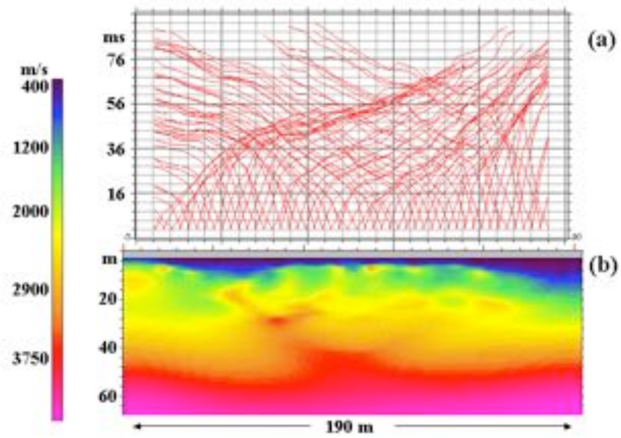

Figure 2. (a) First-arrival times picked from the shot gathers along Line P1 used in nonlinear traveltime tomography to estimate the P-wave velocity-depth model shown in (b).

Table 2 shows the workflow for the analysis of Rayleigh waves on the records obtained from the surface-wave profiles S1-S6 to estimate the S-wave velocity-depth profiles (Yilmaz and

Eser, 2002). Along each of the line traverses S1-S6, one of the two end-on shot gathers that exhibits a most pronounced dispersive character for surface waves is selected for the analysis. Following the analysis, the estimated S-wave velocity-depth profiles were assigned to the center station of the lines represented by the green circles S1-S6 in Figure 1.

To compute an accurate and physically plausable dispersion curve from the surface waves, they first are isolated from the refracted and much of the reflected waves by applying a top and bottom mute (Figure 3a). The processed surface waves are then used to perform plane-wave decomposition to pick the dispersion curve associated with the fundamental mode of the Rayleigh waves as shown in Figure 3b. By applying the inversion procedure (Park et al., 1999; Xia et al., 1999) to the dispersion curve in Figure 3b, an S-wave velocity-depth profile is estimated as shown in Figure 3c.

Table 2. Workflow for analysis of surface waves.

1	Isolate the surface waves on the records by inside and outside muting.
2	Perform plane-wave decomposition to transform the data to phase-velocity versus frequency domain.
3	Pick the dispersion curve associated with the fundamental mode of the Rayleigh-type surface waves.
4	Perfom inversion of the dispersion curve to obtain the shear-wave velocity as a function of depth.

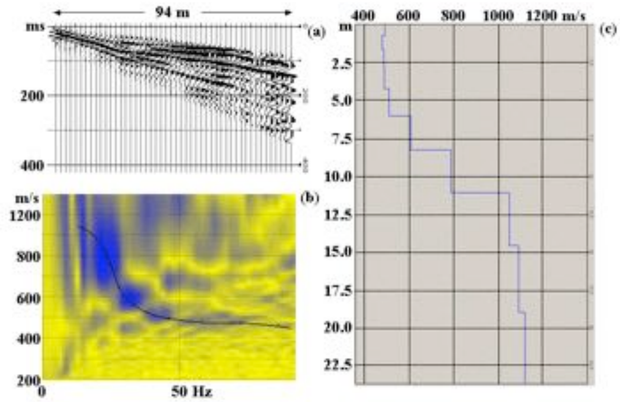

Figure 3. (a) A shot record from Line S1 with isolated Rayleigh-type surface waves. (b) Plane-wave decomposition of the surface-wave package shown in (a). The dispersion curve for the fundamental mode is picked as shown here and used in the inversion procedure to estimate the shear-wave velocity-depth profile shown in (c).

4. INTERPRETATION

The near-surface at the site comprises three main units starting from the ground level (Figures 4-8): (1) Top soil and/or fill with V_p varying between 500-1,000 m/s and thickness varying between 3-18 m; (2) a heterogeneous layer with V_p varying between 1,000-2,500 m/s in most parts of the site and thickness varying between 10-35 m; (3) a relatively homogeneous layer with V_p varying between 2,500-3,500 m/s, mostly in the vertical direction, and thickness varying between 10-20 m.

Below the near-surface layers is the geological bedrock with V_p exceeding 3,500 m/s. P-wave velocities generally are 10-20% higher in the NS direction than the velocities in the EW direction, particularly within the third layer and the bedrock. Such directional difference in velocities may be attributed to seismic anisotropy caused by fracture planes in the EW direction that may be present in the third layer and the bedrock. The depth of the near-surface-bedrock interface varies between 20-45 m. Note that the interfaces between the near-surface units and the near-surface-bedrock interface have a prominent three-dimensional character. Some dikes and faults can also be inferred from the structural interpretation of the P-wave velocity-depth models for Lines P1-P5 based on velocity contrast (Figures 4-8). Correlation of the structural features with *three-dimensional* behavior identified on the *two-dimensional* P-wave velocity-depth models for Lines P1-P5 can only be expected to be less-than-ideal.

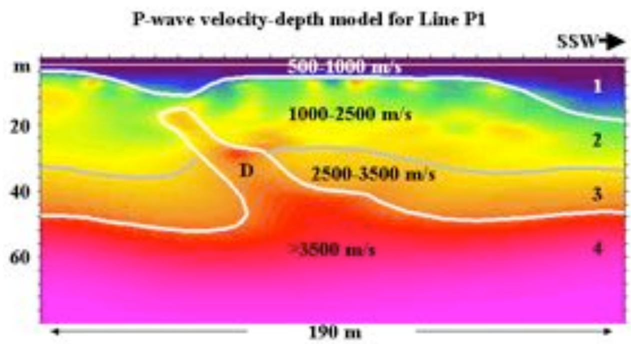

Figure 4. Structural interpretation of the P-wave velocity-depth model for Line P1 with velocity-based layer identification. D is probably a dike. See Figure 1 for the line location.

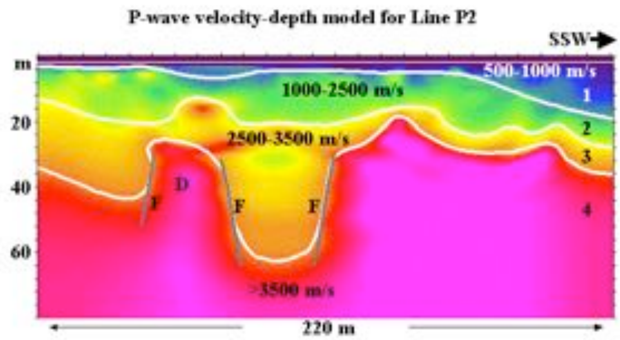

Figure 5. Structural interpretation of the P-wave velocity-depth model for Line P2 with velocity-based layer identification. D is probably a dike and gray lines denoted by F are probably faults. See Figure 1 for the line location.

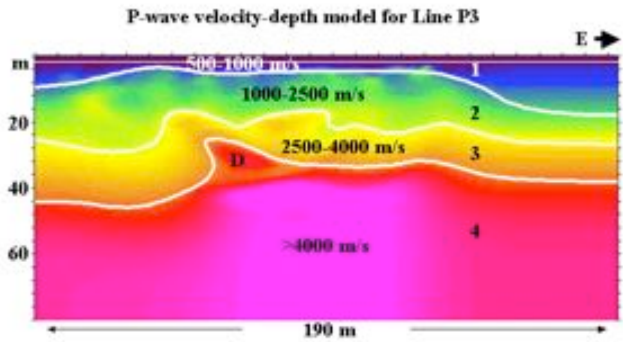

Figure 6. Structural interpretation of the P-wave velocity-depth model for Line P3 with velocity-based layer identification. D is probably a dike. See Figure 1 for the line location.

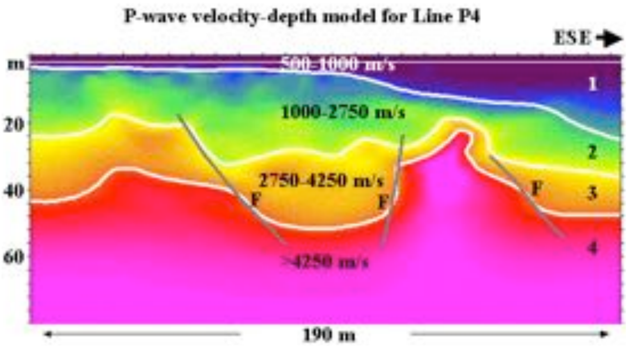

Figure 7. Structural interpretation of the P-wave velocity-depth model for Line P4 with velocity-based layer identification. Gray lines denoted by F are probably faults. The line location is highlighted by the pink solid line on the location map at the bottom right. See text for details.

For geotechnical modeling of the near-surface at the site, velocity strands for 2500, 3000, and 3500-m/s were delineated from the P-wave velocity-depth models for Lines P1-P5. The thickness of the 2,500-m/s velocity layer varies between 15-35 m. Whereas, the thickness of the 3,000-m/s velocity layer varies between 5-15 m with an anomalously thick locality observed on Line P2. The thickness of the 3,500-m/s velocity layer also varies between 5-15 m. Based on average thicknesses and the surface area of the site (36,000 sq.meters), the total volumetrics of the three layers are 900,000, 360,000, and 360,000 cubic meters, respectively.

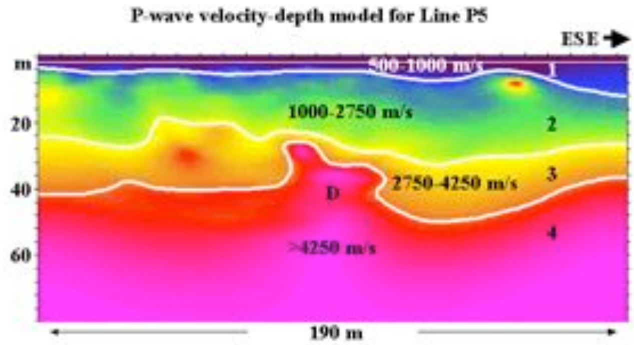

Figure 8. Structural interpretation of the P-wave velocity-depth model for Line P5 with velocity-based layer identification. D is probably a dike. The line location is highlighted by the pink solid line on the location map at the bottom right. See text for details.

The S-wave velocities vary between 300-600 m/s at the ground level. The maximum depth at which the S-wave velocity reaches 700 m/s value can be considered as the soil-geotechnical bedrock interface (Figure 9). The depth of this soil-bedrock interface at the site varies between 6-22 m from the ground level.

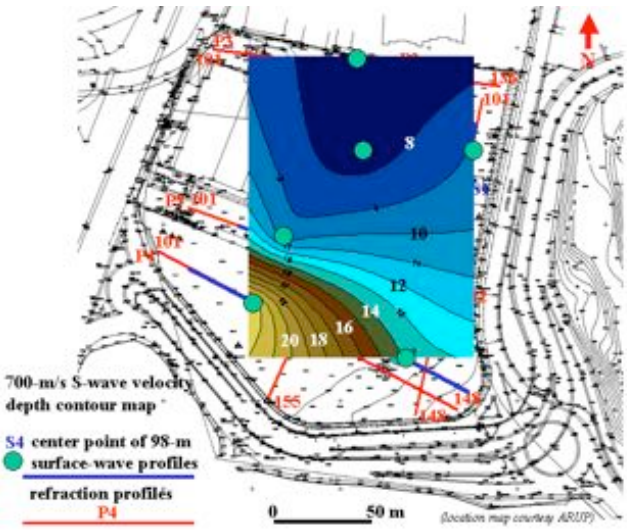

Figure 9. Depth contour map for 700-m/s S-wave velocity over the site created from the S-wave velocity-depth curves at Locations S1-S6 (highlighted by the solid green circles). Contour values are in meters measured from the ground level.

5. CONCLUSIONS

An integrated shallow seismic survey is conducted for site investigation at the future site of a tower structure site requested. 48-channel seismic records are acquired along five line traverses using common-spread geometry with 4-m shot interval and 4-m geophone interval. The P-wave velocity-depth models are estimated by nonlinear inversion of the first-arrival times picked from the recorded shot gathers. The geometry of the layers within the near-surface and that of the near-surface-bedrock interface are defined based on P-wave velocity variations along the line traverses. Additionally, by using a receiver spread with 48 geophones at 2-m intervals, three shot records; two at the end and one at the center of the spread are acquired. The S-wave velocity-depth profiles are estimated by inversion of Rayleigh-type surface waves observed on the recorded shot gathers. Shear-wave velocity-depth profiles at six locations within the site are also obtained.

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P-wave velocities generally are 10-20% higher in the NS direction than the velocities in the EW direction, particularly within the third layer and the bedrock. Such directional difference in velocities may be attributed to seismic anisotropy caused by fracture surfaces in the EW direction that may be present in the third layer and the bedrock.

The depth of the near-surface-bedrock interface varies between 20-45 m. The interfaces between the near-surface units and the near-surface-bedrock interface have a prominent three-dimensional character. Some dikes and faults can also be inferred from the structural interpretation of the P-wave velocity-depth models based on velocity contrast.

Velocity strands for 2500, 3000, and 3500-m/s delineated from the P-wave velocity-depth models can be used for geotechnical modeling of the site. The maximum depth at which the S-wave velocity reaches 700 m/s value can be considered as the soil-geotechnical bedrock interface. The depth of this soil-bedrock interface at the site varies between 6-22 m from the ground level.

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