Evaluation of shear wave velocity distribution map using SPT-uphole tomography method

L'évaluation de carte de distribution de vitesse de signe de tondage en utilisant la méthode de tomographie de SPT-uphole

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ABSTRACT

The standard penetration test (SPT) is common in geotechnical site investigations and is a useful and economical tool for uphole seismic tests. Here, the SPT-uphole method was applied to the creation of a subsurface shear wave velocity (V_S) distribution map. Field testing with several surface geophones in line from a drilling point, combined with data interpretation using tomography inversion, resulted in a triangular-shaped subsurface V_S distribution map. The particle motions due to the SPT source were examined using a numerical study, from which the procedure was derived. Magnitude summation of the vertical and horizontal components was proposed to more accurate and conveniently calculate the travel times of shear wave component in the recorded signals. Field application tests were performed at two sites to establishment the method and to verify its feasibility. The SPT-uphole tomography method provides a reliable two-dimensional V_S distribution map that compares with the results of SPT and a resistivity survey.

RÉSUMÉ

Le test de penetration standard (SPT) est commun dans les enquêtes de site géotechnique et est un instrument utile et économique pour les tests sismiques uphole. Ici, la méthode SPT-uphole a été appliquée à la création d'une vitesse de signe de tondage sous de surface (CONTRE) la carte de distribution. Le test sur place avec plusieurs surface geophones à la ligne d'un poind de forage, combine avec l'interprétation de données en utilisant l'inversion de tomographie, s'est ensuivi dans une sous-surface en-forme-de-triangulaire CONTRE la carte de distribution. Les mouvements de particule en raison de la source SPT ont été examines en utilisant une étude numérique, dont la procédure a été tirée. La somme d'étendue des composantes verticales et horizontales a été proposée à plus exact et calculer de façon pratique les temps de voyage de composante de signe de tondage dans le signal enregistré. Les épreuves d'application de terrain ont été executes à deux sites à l'établissement la method et verifier sa faisabilité. La méthode de tomographie SPT-uphole founit un deux dimensionnelle sûr CONTRE la carte de distribution qui est comparable avec les résultats de SPT et une enquête de résistivité.

Keywords : SPT, uphole seismic method, site characterization, imaging technique, shear wave velocity

1 INTRODUCTION

Measurement of the shear wave velocity (V_S) near the subsurface are important in geotechnical engineering practice, since they can provide input to seismic design methods such as site response analysis and the evaluation of liquefaction potential. V_S can also be used for static deformation problems induced by excavation and settlement (Stokoe et al. 2001). Moreover, as V_S represents the material and structural conditions of the site, it can be applied to the evaluation of layer structures, degree of compaction or consolidation of a soft soil and weak zones of a site (Kim & Park 1999; Chang et al. 2006).

The standard penetration test (SPT) is a frequently used method in geotechnical site investigation. A modified uphole method, the SPT-uphole method, was introduced as an effective technique to obtain the V_S profile of a site. A schematic diagram of this method is shown in Figure 1 (Bang & Kim 2007). The split spoon sampler is penetrated into the soil by hammering, resulting in a significant amount of compression and shear waves generated at the tip and side. By placing a series of receivers on the ground surface, it is possible to perform an uphole test during SPT, which is usually performed at 1 or 1.5 meter intervals. The boring and SPT are performed simultaneously; thus, the SPT-uphole method can occur during boring without inducing additional cost. The method is very simple and economical, and it is not labor intensive. It eliminates the need to prepare the cased testing hole with grouting, and also eliminate the labor intensive sourcing work required by other borehole seismic methods.

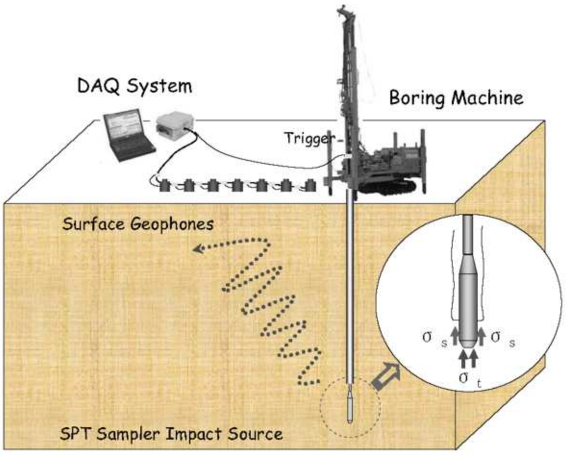

Figure 1. Schematic diagram of the SPT-uphole test.

The conventional SPT-uphole method was introduced to construct a one-dimensional V_S profile. However, if a two-dimensional data interpretation method is adopted such as tomography inversion, then a triangular shaped subsurface V_S distribution map can be developed. An adequate tomography inversion procedure should be employed, and it is importance to estimate the exact first arrival time. This is a very attractive enhancement to the technique, since multi-dimensional subsurface images can be obtained using boring without introducing additional costs.

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To understand particle motions caused by the SPT source, a numerical study was performed and a procedure was introduced to perform the SPT-uphole method for subsurface V_S imaging (SPT-uphole tomography method). A procedure using magnitude summation of the vertical and horizontal components was proposed to calculate the travel times of the shear wave component in the recorded signals more exactly and conveniently. Finally, a field application test was performed at two sites to establish the technique and to verify feasibility.

2 UNDERSTANDING PARTICLE MOTIONS DUE TO SPT SOURCE

As the sampler moves downward during impact, it generates a shear (S) wave of vertical motion (SV type) and a compression (P) wave near the source. The major direction of each wave motion will vary depending on the locations of the source and receiver. Both the vertical and radial horizontal motions simultaneously govern the surface motion when the elastic wave is generated by the SPT sampler in the ground.

The results obtained from numerical simulations provide the characteristics of particle motion at the ground surface. Figure 2 shows the particle motion in space (hodograph) in both the vertical and radial horizontal directions. The vertical distances represent the testing depths and the horizontal distances are the distances from the borehole (offsets). The motion of the P-wave component is aligned with the direction of the ray path, and the motion of the S-wave component is perpendicular to the direction of the ray path. The left side of Figure 2 shows an enlargement of the representative particle motions at source depths of 6 m, 15 m, and 24 m and with the receiver location at 8 m. It can be seen that the direction of the P and S-wave particle motions changes according to the location of the source and receiver. Thus, the use of two-component (radial horizontal and vertical) geophones is recommended to obtain better travel time information for the SPT-uphole method, even though typically only vertical component geophones are used in surface seismic methods.

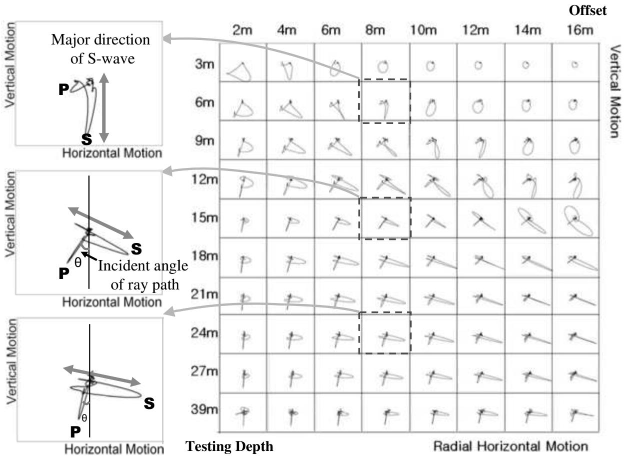

Figure 2. Characteristics of the particle motion on the ground surface in a space domain consisting a vertical and a radial horizontal direction.

3 TESTING PROCEDURE AND DATA REDUCTION

The SPT-uphole tomography method can be considered to be a borehole-to-surface traveltime tomography using impact energy during SPT as a source. The method is composed of three steps. The first step is data acquisition (to obtain signals from the field test), the second step is signal processing (to determine the first arrival travel times of the shear wave), and the last step is inversion analysis (to construct subsurface imaging).

The surface geophones are placed on the ground at selected intervals from the boring point. Better results are achieved as more receivers are used. Additionally, the use of two-component (radial horizontal and vertical) geophones is recommended to obtain better travel time information. Figure 3 shows the signal traces of the vertical and horizontal components at each distance when the depth of source is 3 m, 18 m, and 39 m, respectively. These traces are obtained from the numerical simulation of Figure 2. The right side of the figure shows the root mean square signals of the vertical and horizontal components in the time domain (two-component signals). The first peaks of the shear wave in these signals (dot points) coincide with the first peaks of the shear wave in the hodograph of Figure 2. Single component signals often do not provide enough information to estimate the shear wave component. Although, from these root mean square signals, the first peak travel times (t_p) can be determined across the entire depth and offsets without the need for subjective judgment.

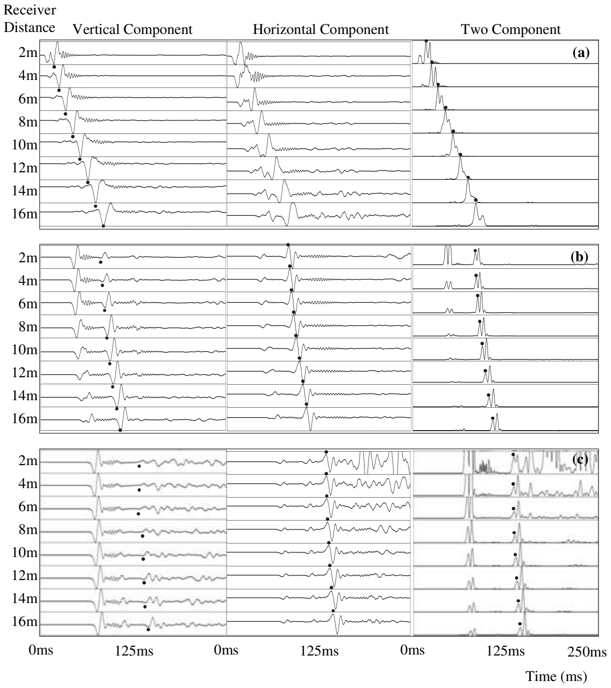

Figure 3. Signal traces at each receiver generated by a numerical simulation of the SPT-uphole method with source depth of (a) 3m, (b) 18m, (c) and 39m. The dot indicated the first peak of the shear wave component.

Many methods have been introduced to estimate the first arrival travel time. In this study, a dominant frequency around the first peak point of the S wave is used to correct the first peak travel time (t_p) and determine the first arrival travel time (t_i). The initial arrival is estimated to be a point that is one quarter period ahead (t_c) of the peak point. When the signals are inadequate for finding the dominant frequency and it is necessary to select the first arrival points manually, the root mean square signals can still be very useful to reliable find the first arrival point of the shear wave. As the travel times are calculated from signals with different trigger locations, a correction for an inconsistent trigger should be considered. The trigger system is normally installed below the anvil, as it is highly impractical to install a trigger system at a sourcing point during the SPT. The length of the rod changes with the different testing depths, so that the corrected travel time, t_t (length of SPT rod/wave velocity of rod) must be subtracted from the measured travel time. Thus, the first arrival travel time (t_i) for the tomography inversion can be calculated using the following equation: $t_i = t_p - t_c - t_t$.

The distribution of the shear wave velocity can be determined by a traveltime tomography inversion. Several traveltime tomography programs have been introduced and commercialized by geophysicists; one of these, GeoTomCG, was used for this study (Tweeton et al. 1992). It was verified using the theoretical traveltime information through the forward modeling of several soil models. This involved the modification of an arbitrary initial velocity model by repeated cycles of three steps: (1) forward computation of a model of first arrival travel times, (2) calculation of travel time residuals, and (3) application of velocity corrections. The inversion of travel time data used a variation of the SIRT algorithm (Lytle et al., 1978).

4 FIELD APPLICATION

Field tests were performed to verify the applicability of the SPT-uphole tomography method. Figure 4 shows a schematic diagram of the testing site at Kimje, Korea. All six borings were drilled to a depth of 13.5 m for the evaluation of the horizontal nonhomogeneity characteristic. The measured N-value was adjusted to N_{60} considering the energy ratio of each SPT equipment. To effectively illustrate the horizontal variation of the layers, the V_S distribution map was constructed using the empirical relationship between the SPT-N value and the shear wave velocity suggested by Imai et al. (1982). As seen in Figure 5, the shape of layers in this site is inclines upward, and the estimated V_S is about 200–300 m/s.

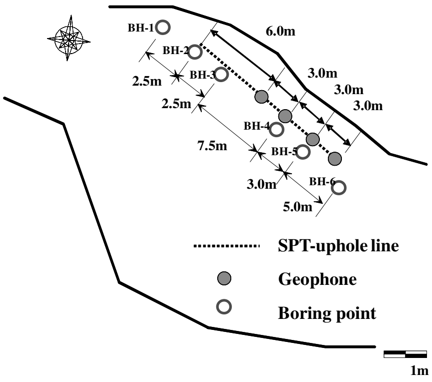

Figure 4. A schematic diagram of the Kimje testing site.

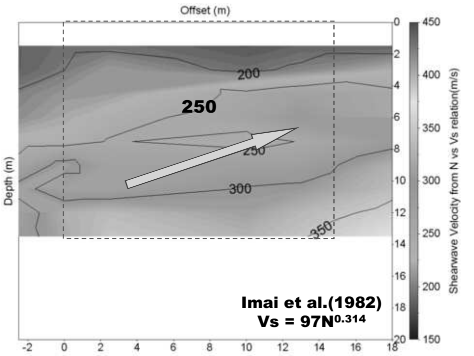

Figure 5. V_S distribution map determined by SPT-N vs. V_S using the empirical relationship of Imai et al. (1982).

Four vertical component geophones were used at this site. The location of each receiver was 6 m, 9 m, 12 m, and 15 m from the boring point (BH-2) and the boring was performed to the depth of about 20 m, especially for the uphole test. The interval used for SPT was about 1.5 m. Signal traces obtained from each receiver are shown in Figure 6, along with the source depth. The travel time information for the shear wave was obtained using the peak point of the vertical component only. The P wave component can easily interfere with the signals recorded by vertical receiver at deep depths of the near receiver as shown in Figure 6a. Therefore, it is desirable to use two component receivers in the field to compensate this problem, by providing a horizontal component. In this case, the testing depth was not deep and only several data samples had interference from the P-wave component; those data were excluded from the tomography analysis.

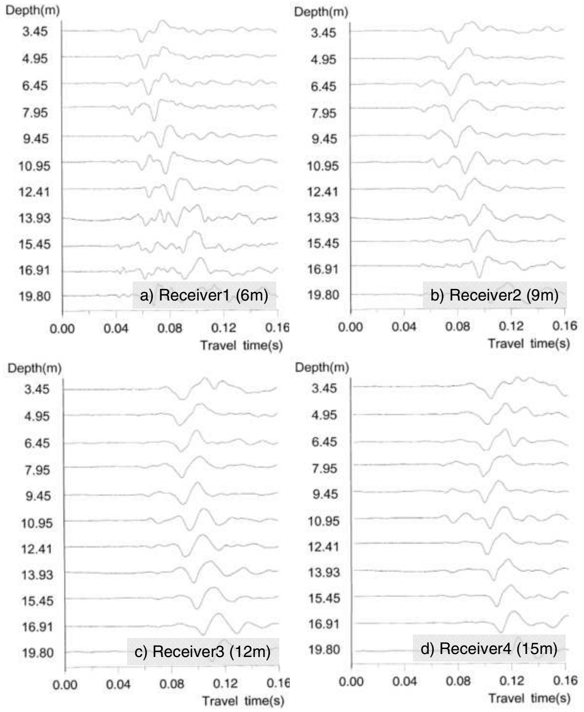

Figure 6. Signal traces at each receiver at the Kimje site.

The shear wave velocity distribution map determined by SPT-uphole tomography is shown in Figure 7. The image is triangular in shape, due to the borehole-to-surface tomography. The V_S distribution is similar to the V_S image obtained by the SPT-N values in Figure 5. It should be noted that the horizontal variation characteristics and a reliable V_S distribution map of the site could be characterized economically by means of the proposed method. The SPT-uphole tomography method shows good potential for the characterization of deformation properties in geotechnical engineering.

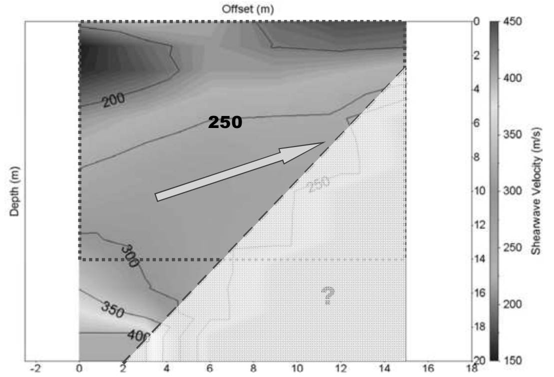

Figure 7. V_S distribution map determined by the SPT-uphole tomography method ; the area of the red dotted rectangle is the same as that in Figure 5.

Another verification field test was performed in Hongsung, Korea. A borehole was drilled to a depth of over 50m to find the boundaries of weathered rock and soft rock. It was found that the weathered zone was very thick with a depth to the soft rock of over 45m. Another borehole was drilled to determine the horizontal variation of the soil layers. Figure 8 shows the assumed result based on the two drilling logs, and overlaid with a picture of the field area. The boundaries of the weathered rock and the soft rock were nearly the same at the two drilling logs. It was assumed that there was no severe horizontal variation, indicating that the underground weathering condition is nearly same around this site.

However, the result of a DC resistivity survey places this assumption in doubt. As seen in Figure 9, the strata around the two boreholes are not simple. The resistivity value is strongly related to the porosity, and it can also be related to the weathering ratio or density. The local resistivity value is also affected by other factors which are not directly related to the soil structure condition, such as the resistivity of water and the resistivity value of the area where the electrodes are installed. It is difficult to interpret the results of the DC resistivity survey quantitatively. Otherwise, the V_S value is directly related to the elastic modulus and it well represents the soil condition; in particular, the weathering ratio.

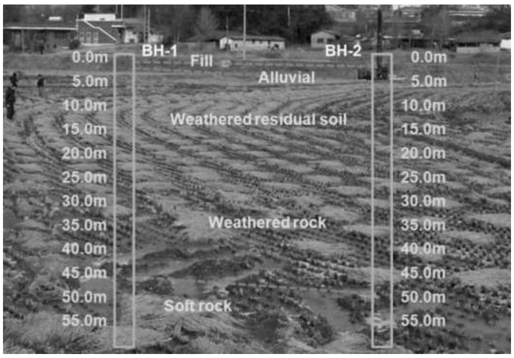

Figure 8. A picture of the field area and an assumed horizontal strata variation based on two drilling logs.

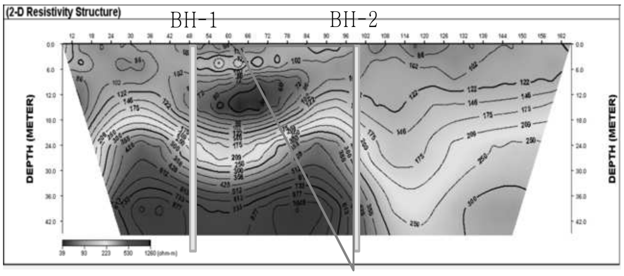

Figure 9. Resistivity distribution map determined by a DC resistivity survey.

It was very difficult to apply a surface seismic method to the construction two dimensional V_S image at this site, because the surface soil condition was submerged and very soft. The SPT-uphole tomography method was performed by the drilling of BH-2 to obtain a subsurface image regardless of the surface soil condition. All twelve units of the two-component geophones were used, with a sourcing interval around 1.5 m. Figure 10 shows the representative signal traces: the vertical, horizontal and root mean square signals, respectively. The signal quality is very good and sufficient for estimating the first arrival point of the shear wave. A subsurface V_S image was constructed as shown in Figure 11. From this image, it was seen that the horizontal strata variation (weathering ratio) is not simple; an additional site investigation is required to exactly determine the boundaries of weathered rock and soft rock at this site.

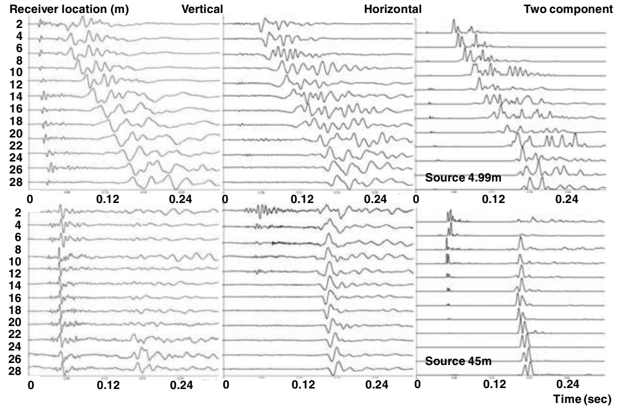

Figure 10. Signal traces at each receiver at the Hongsung site; the upper figures corresponding to a source depth of 4.99 m, and the lower figures to a source depth of 45 m.

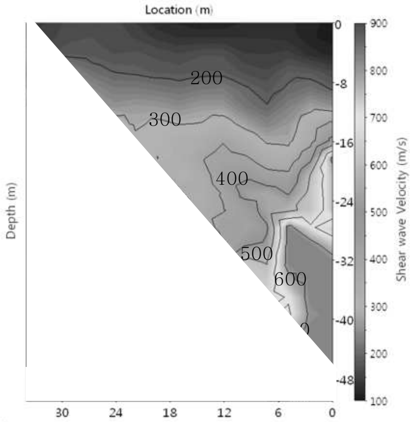

Figure 11. V_S distribution map determined by the SPT-uphole tomography method at the Hongsung site.

5 CONCLUSION

An SPT-uphole tomography method was proposed. Field testing occurred using several surface geophones in line from a drilling point. The data interpretation with tomography inversion resulted in a triangular-shaped subsurface V_S distribution map. Through numerical study and field application tests, the proposed method was established and its feasibility was verified.

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