

Evaluation of Near Subsurface Vs Distribution Map Using SPT-Uphole Tomography Method

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Summary

SPT-Uphole tomography method was introduced for the evaluation of near subsurface shear wave velocity (Vs) distribution map. In SPT-Uphole method, SPT (Standard Penetration Test) which is common in geotechnical site investigation was used as a source and several surface geophones in line were used as receivers. Vs distribution map which is the triangular shape around the boring point can be developed by tomography inversion. To obtain the exact travel time information of shear wave component, a procedure using the magnitude summation of vertical and horizontal components was suggested based on the evaluation of particle motion at the surface. It was verified that proposed method could give reliable Vs distribution map through the numerical study using the FEM (Finite Element Method) model. Finally, SPT-Uphole tomography method was performed at the weathered soil site where several boring data with SPT-N value are available, and the feasibility of method was verified in field.

Introduction

Shear wave velocity (VS) of near subsurface is very important in geotechnical practice. It is used for not only seismic design such as site response analysis and evaluation of liquefaction potential but also static deformation problems induced excavation and settlement. Besides representation of the material and structural condition of the site, Vs distribution map can be applied for the evaluations of the degree of compaction and consolidation of a soft soil, layer structure and weak zone of the site (Kim and Park, 1999).

Various field seismic tests, including both borehole (invasive) and surface (non-invasive) tests, are used to obtain VS profile of a site. Because each test has its own advantages and disadvantages, it is important to select adequate testing technique considering the site condition and importance of project. SPT-Uphole test which is based on SPT (Standard Penetration Test) is a modified version of uphole test. SPT is most frequently used in site investigation. Because the impact energy generated by penetration of sampler in the soil produces the significant amount of SV type shear waves in depth, the proposed method can provide a VS profile with boring simultaneously (Bang et al., 2001).

In this paper, authors introduced SPT-Uphole tomography method to evaluate VS distribution map which is triangular shape around the boring point using the travel time between borehole and surface. The factors for obtaining reliable result using SPT-Uphole tomography method are the determination of the exact travel time information and the application of the accurate tomography inversion method. Tomography inversion methods have been studied and programmed for decades by many researchers in geophysics. Therefore, this study has been focused on the method for obtaining exact travel time information. Travel times are determined by both Finite element method (FEM) and theoretical travel time information generated by ray tracing method based on Snell's Law using representative soil model, and the applicability of SPT-Uphole tomography method was assessed. Finally, the proposed method was applied at the weathered soil site in Korea and the feasibility of the proposed method was verified in the field.

Characteristics of particle motion at the ground surface due to SPT impact source in depth

Understanding of the wave types generated by SPT sampler is crucial for the development of SPT-Uphole

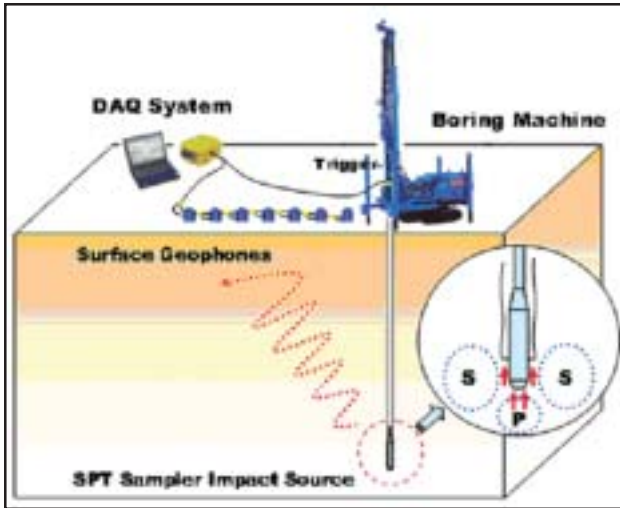


Fig. 1: Schematic diagram of the SPT-Uphole test.

tomography method. Because the sampler moves downward during the impact, it can be postulated that the shear wave of the particle motion in vertical direction (SV type wave) is generated and propagating horizontally, and the generated compression (P) wave is propagating in the vertical direction near the sampler as shown in Fig. 2. P-wave component will be mainly detected in the radial direction on the ground surface when SPT source is located at shallow depth while it will be mainly detected in the vertical direction at deep depths. On the contrary, since the vertical motion of SV type wave changes to horizontal motion as propagating vertically, S-wave component will be mainly detected in the vertical direction on the ground surface when SPT source is located at shallow depth and mainly detected in the radial direction when located at deep depths. This effect is grown in the case that the ray path is refracted when the stiffness lessens to the surface (Kim et al., 2004a). That is to say, the major direction of each wave motion will vary depending on the

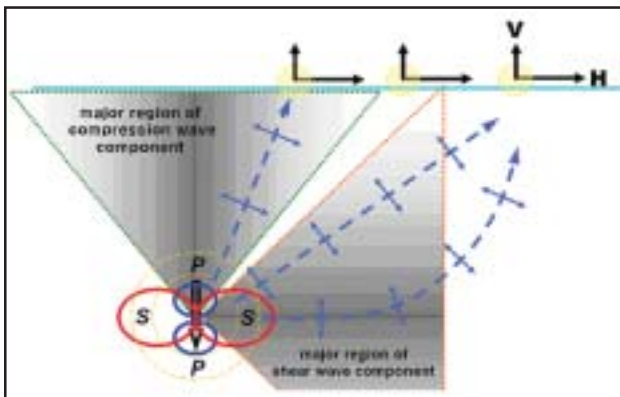


Fig. 2: The major region and direction of P and S-wave generated by SPT impact source.

location of source and receiver. In result, it is thought that both vertical and radial horizontal motion is governing simultaneously the surface motion when the elastic wave is generated by vertical source in depth.

In order to investigate the types of waves generated by SPT sampler in the real condition, numerical study using ABAQUS Standard was performed. As shown in Fig. 3, two layers model that has different shear wave velocity in each layer was designed. To simulate the condition of in depth SPT impact source which is generated at one point and propagates spherically without reflecting effect at the end-boundary of model, axis-symmetric 4 node element (CAX4) with infinite element (CINAX4) was implemented. The size of the element was $0.1\text{m} \times 0.1\text{m}$ and calculation time step were determined 0.0005sec as proposed by Zerwer et al. (2002). Imaginary seven vertical and horizontal component geophones were located on the ground surface with the spacing of 2m to the distance of 18m and the particle motions were recorded during 0.1sec after vertical impact sourcing. The shape of wave propagation at the time of 0.0365sec was contoured in Fig. 4. It is well presented that compression (P) wave and shear (S) waves propagate spherically.

Exact determination of initial arrival of shear wave is somewhat difficult in SPT-Uphole test because the polarity characteristics of S-wave cannot be used. The typical signal

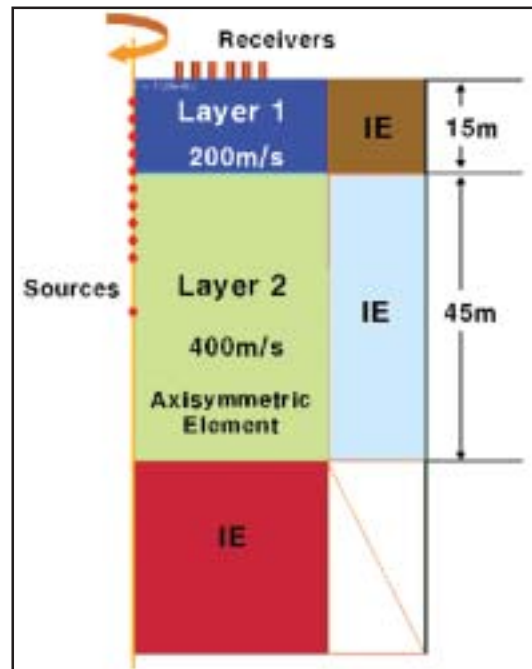


Fig. 3: Numerical model for FEM analysis to predict particle motion at the surface due to in depth vertical source.

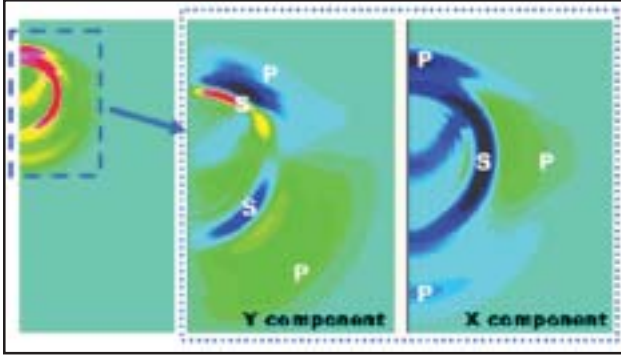


Fig. 4: The shape of wave propagation at the time of 0.0365sec after sourcing.

traces of vertical and horizontal components in the time domain are shown in Fig. 5. The shear wave components are clearly detected at most of different depths. It is also interesting to notice that P-wave components are arrived earlier and separated by S-wave. In the case of vertical motion, the shear wave arrival is confused by the early P wave as increasing source depth. In the case of horizontal

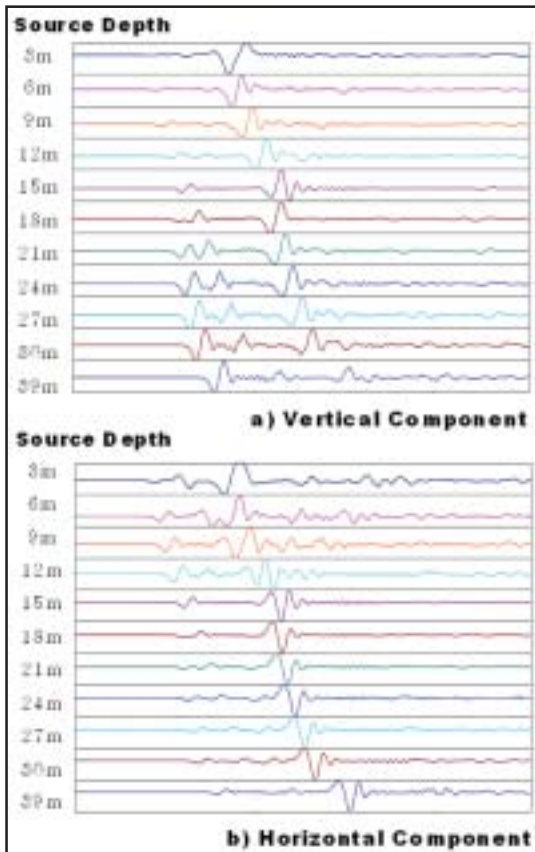


Fig. 5: The signal traces in time domain with depth at the receiver location 8m.

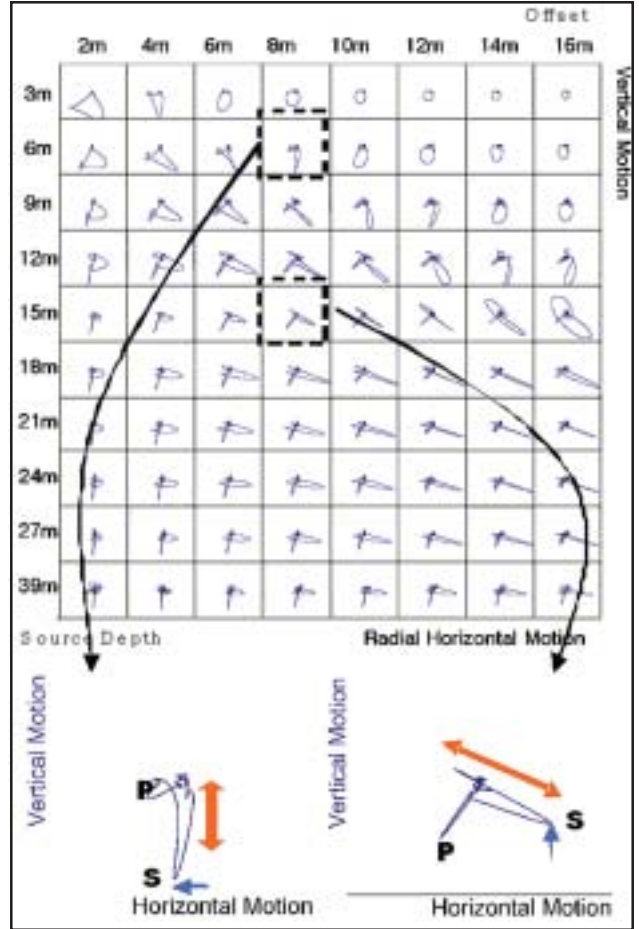


Fig. 6: The characteristics of particle motion at the ground surface in space domain.

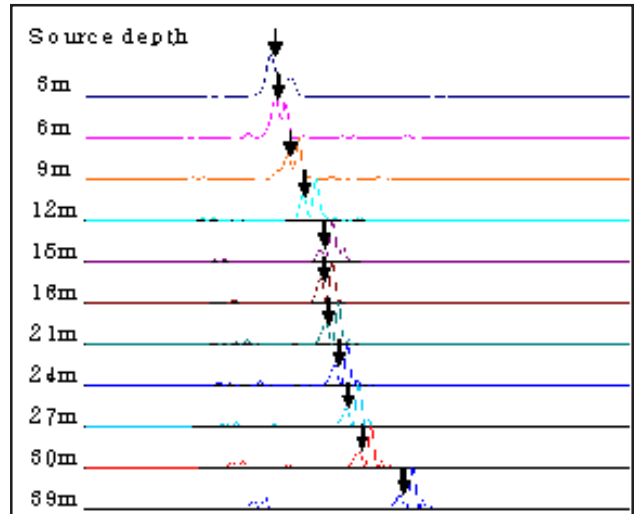


Fig. 7: The root mean square value signals of vertical and horizontal component in time domain with depth at the receiver location 8m .

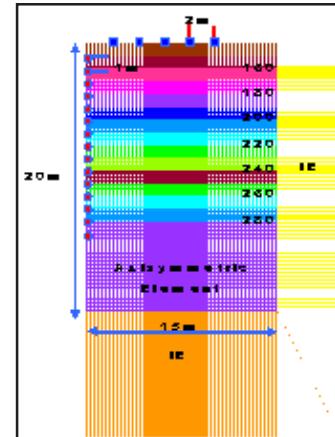


motion, the shear wave arrival is not clear at shallow depth because of the discordance between sourcing and sensing directions. It can be well understood from the characteristics of particle motion at the ground surface as shown in the Fig 6. The motion of P wave component is same and the motion of the S wave component is perpendicular with the direction between source and receiver. It is shown that the direction of particle motions of P and S waves is changed according to the location of the source and receiver as previously mentioned in the Fig 2. Therefore, the magnitude of horizontal motion increases compared with the magnitude of vertical motion as increasing the depth and distance from boring point. It makes easier to pick the first peak point of S-wave exactly in all case using the vertical and horizontal motion simultaneously. The arrows in the below part of the Fig 6 represent the first peak point of S-wave component. Therefore, in the proposed method, vertical and horizontal radial geophones are used together. In Fig. 7, the root mean square value signals of vertical and horizontal component in time domain were presented and the first peak of shear wave can be discriminated easily without hesitation in the whole depths. However, since the travel time information is not first arrivals of S-wave, the further correction is needed as described in next chapter.

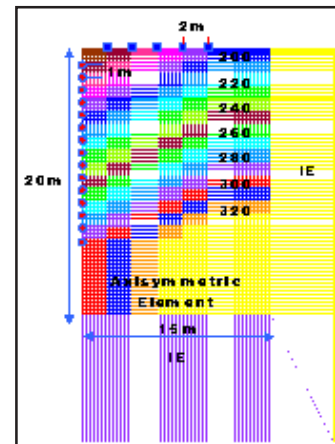
Establishment of SPT-Uphole Tomography Method Using Numerical Study

The proposed SPT-Uphole tomography method is composed of 3 steps. The first step is to obtain signals from field test, the second step is determination of the arrival travel times, and the last step is borehole to surface tomography inversion. To establish the each step in proposed method, numerical studies were performed using FEM modeling. Three models were used to represent three typical ground conditions. Model 1 represents a simple situation with horizontal stacked layers and the Vs value of each layer is increased gradually with depth from 150m/s to 290m/s. The thickness of each layer is 1m excluding the last layer which is described as infinite element. Model 2 and Model 3 represent inclined condition of the Model 1. The Model 2 was inclined upward direction while Model 3 was inclined downward direction. The each configuration of models illustrated in Fig. 8.

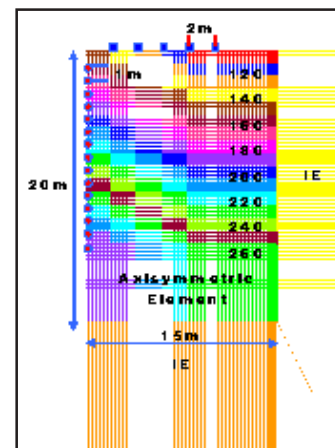
Travel time information of each FEM model was determined as the same manner discussed in previous chapter. Vertical impact loadings simulating SPT source were applied



a) Model 1



b) Model 2



c) Model 3

Fig. 8: Three typical soil model for numerical study. a) horizontal layer model b) upward inclined layer model c) downward inclined model.

at all 15 points with 1m interval and the signals were recorded at 5 receiver points with 2m spacing along the surface. The typical particle motions at the ground surface and the procedure determining the first peak point of the S-wave component and time difference for correction to the first arrival were shown in Fig. 9. As mentioned, the travel time information using the method introduced previous chapter was not the first arrival travel time but the first peak of arrival time of S-wave. In order to corrects the travel time information as the first arrival travel time, the authors used a reference time difference between first peak point and the first arrival of S-wave. As shown in Fig. 9b, some source energy at a given depth can give an obvious arrival of S-wave in both vertical and horizontal components, and this can be used as a reliable reference time difference. All travel time information determined by using peak points can be corrected to the first arrival time information using this representative time difference value if the main frequency content of shear wave is assumed to be similar.

The first arrival travel time for tomography inversion determined by this scheme was plotted in Fig. 10 and compared with the theoretical travel time. The theoretical travel time was computed using shooting ray tracing method based on Snell's Law as shown in Fig. 11. The first arrival times determined from proposed method match well with the theoretical value amazingly.

The shear wave velocity distribution map determined by tomography inversion was shown in Fig 12. The

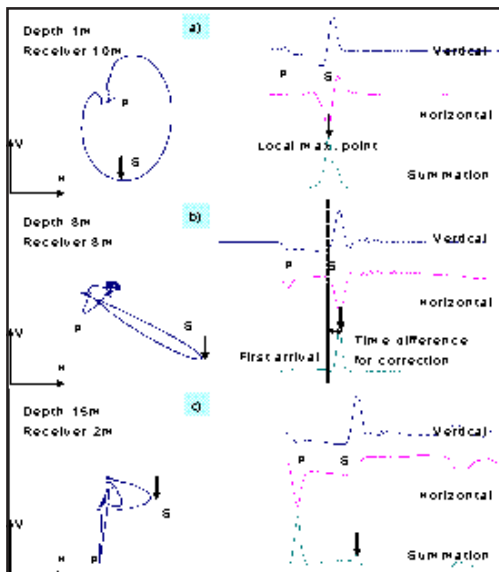


Fig. 9: The representative particle motion at the surface and the procedure to determine first arrival travel time.

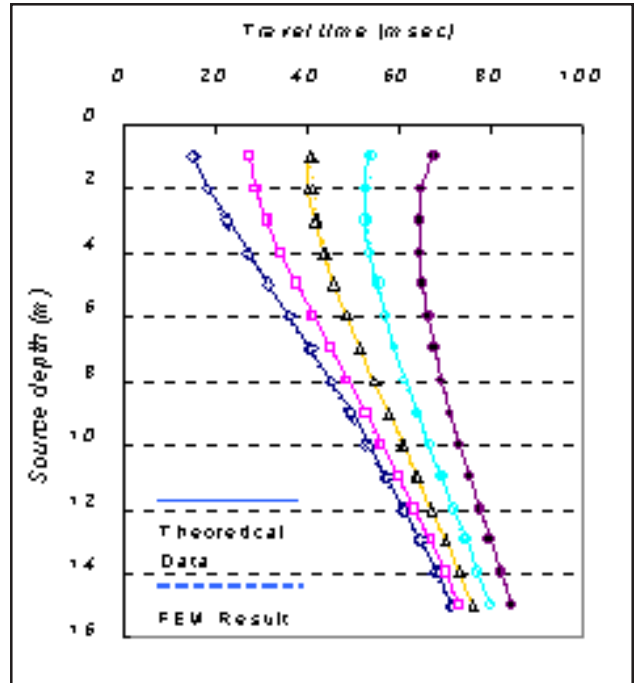


Fig. 10: First arrival time information from FEM analysis compared to theoretical travel time determined by ray tracing (Model 1).

tomography program, GeoTomCG (Tweeton et al., 1992) was used in this analysis. This involves modification of an arbitrary initial velocity model by repeated cycles of three step: forward computation of model of first arrival travel times, calculation of travel time residuals and application of velocity corrections. Curved ray tracing for forward calculation is performed with a revised form of ray bending, derived from the Um and Thurber (1987) and modified in order to improve the reliability of the results of the original formulation for abrupt changes in the velocity gradient. Refraction of wave energy is simulated with the use of wavefront migration, based on Huygens' Principle, thereby suppressing the shadow-zone problem which affects conventional ray-tracing calculations. Inversion of travel time data was made with a variation of the SIRT algorithm (Lytle et al., 1978; Peterson et al., 1985).

Because of the limitation of the borehole-surface travel time tomography, Vs values in the region B and C could not be guaranteed as trust values. Only region A can be used for interpretation of the result, and the results of region A delineated the original model well not only the shape but also the shear wave velocity value. In the case of the Model 2 and 3, the result also had similar quality (Fig. 13 and Fig. 14). From these numerical studies, the proposed SPT-



Uphole tomography method was considered as a potential method for obtaining reliable Vs distribution map in the various conditions of soil sites.

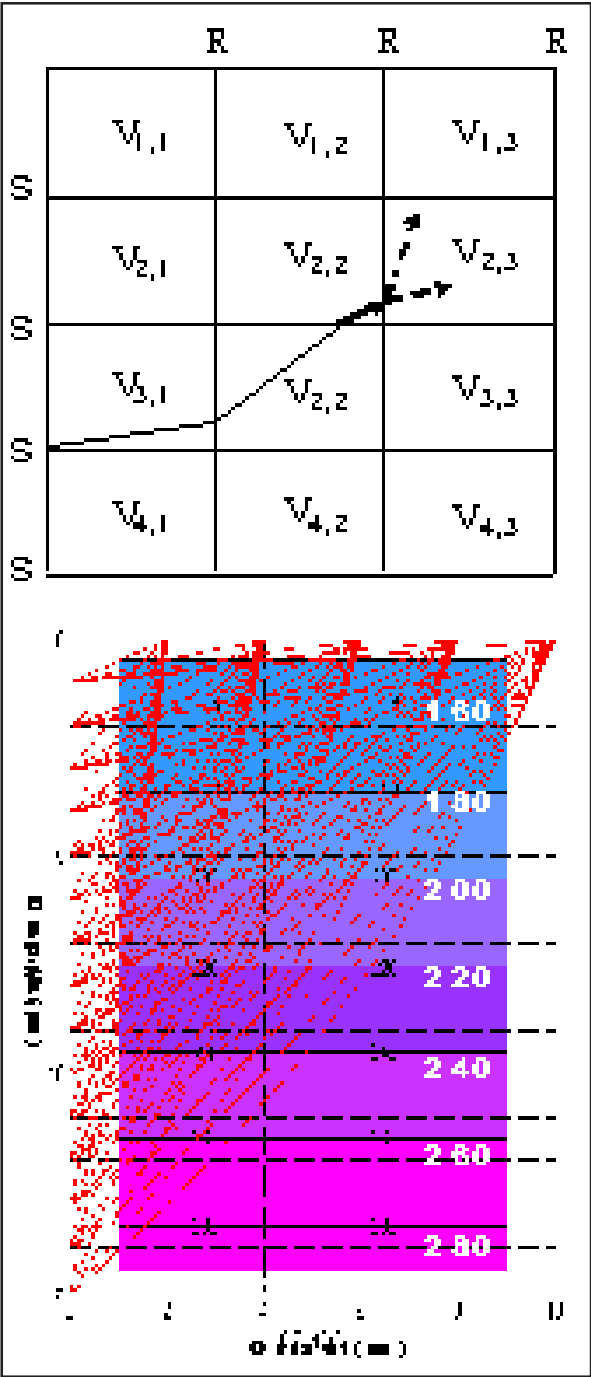


Fig. 11: Ray tracing scheme using the refracted ray path based on the Snell's Law for computing theoretical travel time information (upper) and ray tracing result of the Model 1(lower).

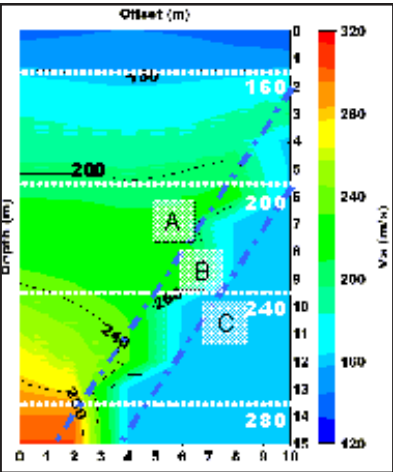


Fig. 12: VS distribution map determined by SPT-Uphole tomography method of Model 1.

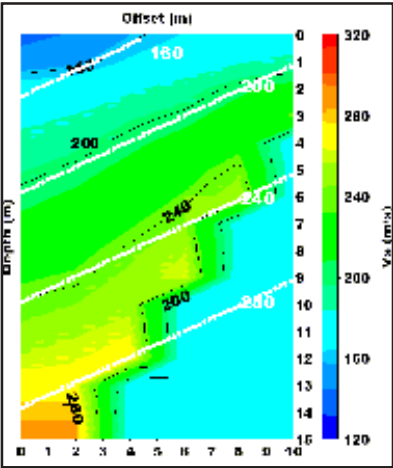


Fig. 13: VS distribution map determined by SPT-Uphole tomography method of Model 2.

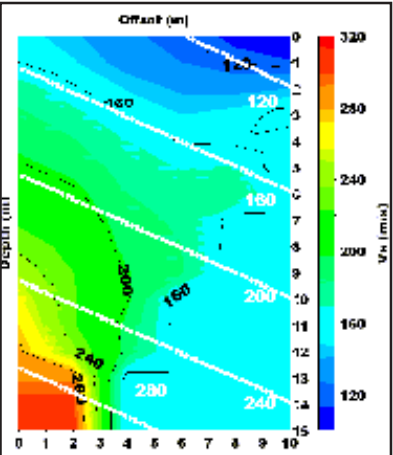


Fig. 14: VS distribution map determined by SPT-Uphole tomography method of Model 3.

Field Application

Field tests were performed to verify the applicability of the proposed SPT-Uphole tomography method. Fig. 15 shows the schematic diagram of SPT-Uphole testing site at Kimje in Korea. All six borings were performed to the depth of 13.5m for evaluation of the horizontal non-homogeneity characteristics and standard penetration tests were also performed. Fig. 16 shows the SPT-N values of each drill log. The measured N-value adjusted to the value with reference energy ratio as N60 considering energy ratio of each SPT equipment (Kim et al., 2004b). To illustrate the horizontal variation of the layers effectively, Vs distribution map was constructed by using the empirical relationship between SPT-N value and shear wave velocity (Fig. 17). It shows that the shape of layers in this site is similar with the Model 2 in numerical studies, upward inclined layers model.

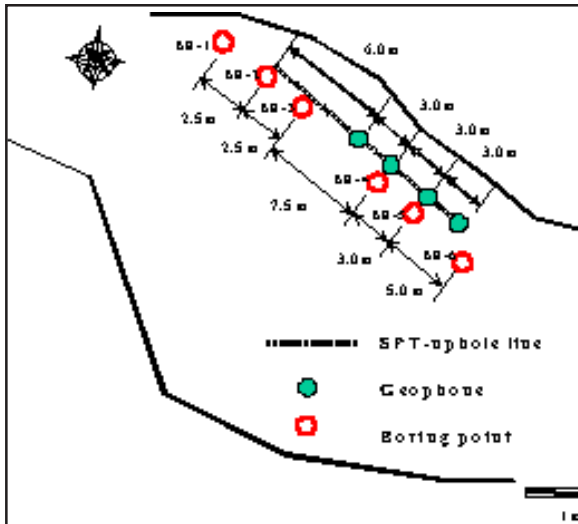


Fig. 15: Schematic diagram of SPT-Uphole testing site.

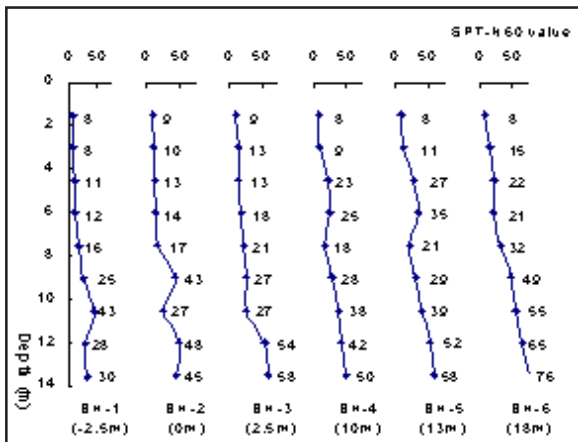


Fig. 16: SPT-N values of the 6 boring holes.

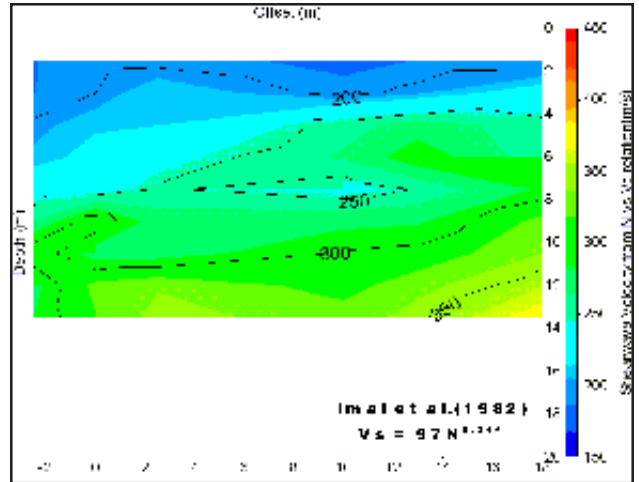


Fig. 17: Vs distribution map determined by SPT-N vs Vs empirical relationship of Imai et al. (1982).

Signal traces are shown in Fig. 18 with the source depth obtained from each receiver at Kim-je site. Unfortunately, only 4 vertical component geophones were used in this study. The location of each receiver was 6m, 9m, 12m, 15m from the boring point (BH-2) and the boring was performed to the depth of about 20m especially unlike the other borings for the proposed method. The travel time information of shear wave was obtained by using the peak point of the only vertical component. From this information, the arrival travel time for tomography inversion was determined by the same scheme established in previous chapter. Because only vertical component geophones were used, first arrivals of shear wave determined using the first peaks of the vertical motion. But, the signals recorded by only vertical receiver can be easily interfered with P wave component especially at the near receivers as shown in Fig 18a. Therefore, it is important to use two component receivers in the field for SPT-Uphole tomography method for compensating this effect by horizontal component. In this case, some of the travel time information that has interference with P-wave component was excluded in the analysis (Fig.19).

The shear wave velocity distribution map which was determined by using the borehole to surface travel time tomography inversion method was shown in Fig. 20. The shape of the shear wave velocity distribution determined by proposed method is similar to that obtained by SPT-N values (Fig. 17). From the depth of 14m in Fig. 20, it is not confident to guess the characteristics of the horizontal variation using the proposed method due to the limitation of borehole to surface travel time tomography. Therefore, it should be performed more deeply than the depth to evaluate the horizontal variation of the site. This field application focused



to the upper region to the depth of 13.5m and SPT-Uphole tomography method was performed to the depth of 20m on this score. Therefore, it should be noted that the horizontal variation characteristics and reliable Vs distribution map of the site could be characterized economically using only 1 boring through the proposed method. It shows the good potential of the SPT-Uphole tomography method for site characterization in geotechnical engineering.

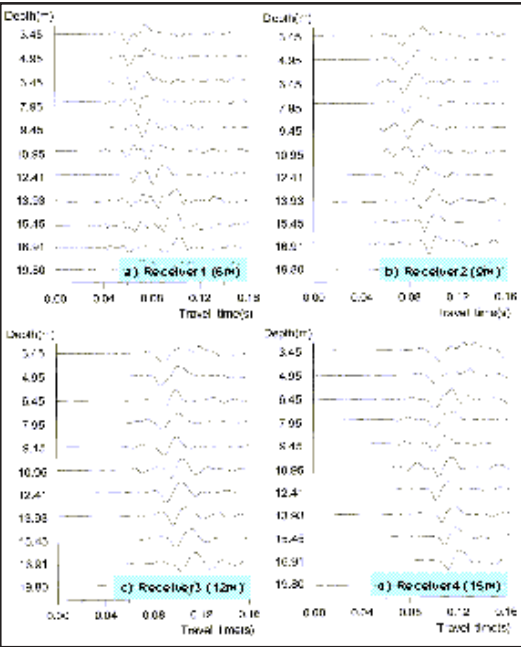


Fig. 18: Signal trace at each receiver in this field application.

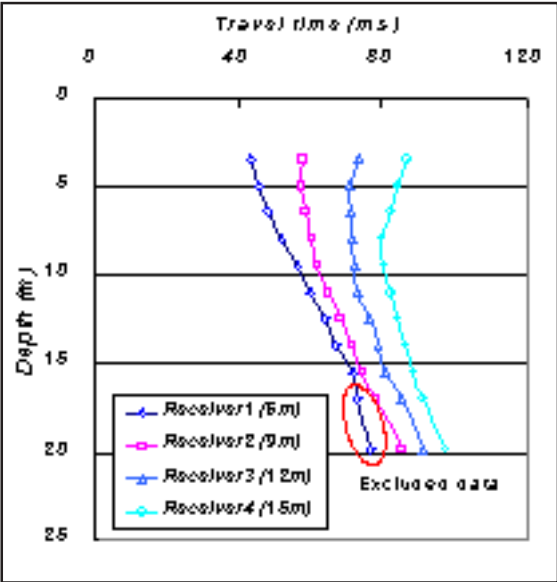


Fig. 19: First arrival time information from this field application and exclusion of some data in the analysis due to P wave infection.

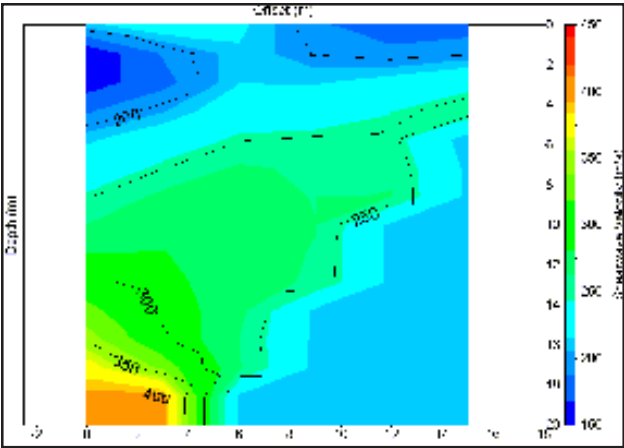


Fig. 20: Vs distribution map determined by SPT-Uphole tomography method.

Conclusions

SPT-Uphole tomography method, which is simple and economical to determine two dimensional shear wave velocity distribution map of the site, was proposed. Testing procedure and interpretation method are introduced. To obtain travel time information, a procedure using the sum of vertical and horizontal components based on particle motion at the ground surface was suggested. Overall procedure of proposed method was verified by using numerical study. Finally, the reliability and applicability of the proposed method were verified in the field by comparing the VS distribution map to SPT-N value distribution from 6 drill logs.

Acknowledgments

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References

Bang, E. S., Kim, D.S., Seo, W. S., 2001, Evaluation of Shear Wave Velocity Profile Using Uphole test, The Fourteenth KKN Symposium Civil Engineering, Kyoto, Japan, pp. 1-4.

Kim, D.S., Bang, E. S., Seo, W. S., 2004a, Evaluation of Shear wave velocity profile using SPT-Uphole method, international site characterization (ISC-2), Porto, Portugal, 1, pp. 339-344.

Kim, D.S. and Park, H.C., 1999, Evaluation of Ground Densification using SASW Method and Resonant Column Tests, Canadian Geotechnical Journal, 36, pp. 291-299.

- Kim, D.S., Seo, W. S., Bang, E. S., 2004b, Energy Ratio Measurement of SPT Equipment, international site characterization (ISC-2), Porto, Portugal, 1, pp. 339-344.
- Lytle, R.J, K.A. Dines, E.F. Laine, and D.L.Lager., 1978, Electromagnetic Cross-Borehole Survey of a Site Proposed for an Urban Transit Station, UCRL-52484, Lawrence Livermore Laboratory, University of California.
- Peterson, J.E., Paulson, B.N.P., McEvilly, T.V., 1985, Applications of algebraic reconstruction techniques to crosshole seismic data, *Geophysics*, 50, 1566-1580
- Tweeton, D.R., 1999, GeoTomCG, Three Dimensional Geophysical Tomography, GeoTom LLC, USA
- Um, J. and Thurber, C., 1987, A Fast Algorithm for Two-Point Seismic Ray Tracing, *Bull. Seismol. Soc. Am.*, 77, 972-986.
- Zerwer, A., Cascante, G. and Hutchinson, J. , 2002, Parameter Estimation in Finite Element Simulations of Rayleigh Waves, *Journal of Geotechnical and Geoenvironmental Engineering*, 128, pp. 250-261