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# A Comparative Study on Borehole Seismic Test Methods for Site Classification

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**ABSTRACT**

In this study, crosshole seismic test, donwhole seismic test, SPT uphole test, and suspension PS logging (SPS logging) were conducted and the shear wave velocities of these tests were compared. The test demonstrated the following result: Downhole tests showed similar results compared to those of crosshole tests, which is known to be relatively accurate. SPS logging showed reliable results in the case of no casing, i.e. in the rock mass, while, in the case of soil ground, its values were lower or higher than those of other tests. SPT-uphole tests showed similar results in the soil ground and upper area of rock mass compared to other methods. However, reliable results could not be obtained from these tests because SPT sampler could not penetrate into the rock mass for the tests.

**Key words:** Shear Wave Velocity, Crosshole Seismic Test, Donwhole Seismic Test, SPS Logging, SPT Uphole Test

## 1. Introduction

The seismic design standard for building structures currently in effect in Korea (Table 1, The Ministry of Land, Transport, and Maritime Affairs, 2005) distinguishes different technical types of ground on the basis of average speed of shear wave velocity in upper 30m of ground. And the standard applies different design response spectra to each ground type to calculate the seismic load on the building. The standard sets forth 6 ground types: $S_A$, $S_B$, $S_C$, $S_D$, $S_E$, and $S_F$. There is no KS standard, however, for measurement of shear wave velocity, and reliability and applicability of most test methods have not been provided.

A wide variety of elastic wave test methods are widely used to investigate ground layers. These test methods may produce different results depending on their unique characteristics, and even the same method can yield different results depending on what equipment is used and who interprets it (e.g. Stokoe et al., 2004). Construction/Building designers are bound to spend quite a lot of time choosing which result to apply to his/her design. Also, different design variables lead to different design outcomes even for building structures built in the same site. Therefore, we need to have a good understanding of the different results that may be produced by different elastic wave test methods to evaluate shear wave velocity in ground, and how to apply thus

Table 1. Site Classification (The Ministry of Land, Transport and Maritime Affairs, 2005)

| Type | Ground Type | Ground Characteristics of Upper 30m Section | | |
|---|---|---|---|---|
| | | Shear Wave Velocity $V_{s,30}$ (m/s) | Blow/foot | Undrained Shear Strength $S_u$ (kPa) |
| $S_A$ | Hard Rock | over 1500 | - | - |
| $S_B$ | Normal Rock | 760～1500 | | |
| $S_C$ | Soil Ground with High Density or Soft Rock | 360～760 | over 50 | over 100 |
| $S_D$ | Hard Soil Ground | 180～360 | 15～50 | 50～100 |
| $S_E$ | Soft Soil Ground | under 180 | under 15 | under 50 |
| $S_F$ | Requires evaluation method specific to the site | | | |

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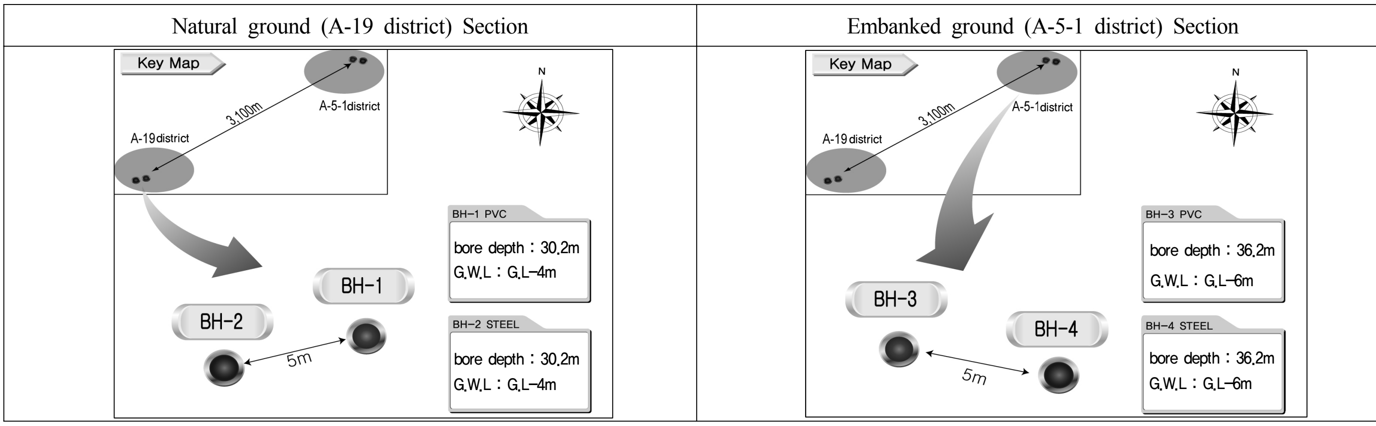



Fig. 1. Borehole Test Position

acquired dynamic physical properties to construction design.

In this study, we selected one site with natural ground and another site with embanked ground from the actual construction sites, where we conducted tests on shear wave velocity using borehole seismic test methods widely used in construction sites which can be applied to soil investigation: crosshole seismic test, donwhole seismic test, SPT uphole test, and suspension PS logging (SPS logging). And we conducted comparative analysis on the shear wave velocity column map required through the above process.

## 2. Results of the Borehole Seismic Tests

### 2.1 Location of Borehole Investigation

For the borehole seismic tests, we selected sites from natural ground and embanked ground within Gyeonggido New-town construction site. Natural ground refers to ground in its natural condition before site arrangement, while embanked ground is a ground filled up as high as 7m on average in order to create foundation. Figure 1 shows the location of borehole investigation, where we divided the test site into two sections: natural ground and embanked ground, and bored holes at two positions in each section. The spacing between boreholes were 5 meters in both sections, which is the maximum distance for acquiring data of good quality from elastic wave tests in boreholes.

### 2.2 Results of the Borehole Investigation

Borehole investigation was conducted on 4 locations: BH-1

Table 2. Depth of Each Layer (Unit : m)

| Position | Borehole | Fillup Layer | Sedimentary | Weathered Soil | Weathered Rock | Soft Rock | Hard Rock | Total |
|---|---|---|---|---|---|---|---|---|
| Natural ground (A-19) | BH-1 | 1.8 | - | 10.7 | - | 1.0 | 16.7 | 30.2 |
| | BH-2 | 1.8 | - | 12.0 | - | 0.9 | 15.5 | 30.2 |
| Embanked ground (A-5-1) | BH-3 | 7.2 | 7.8 | 6.0 | 9.0 | 4.1 | 2.1 | 36.2 |
| | BH-4 | 7.3 | 7.7 | 7.0 | 6.0 | 2.7 | 5.5 | 36.2 |

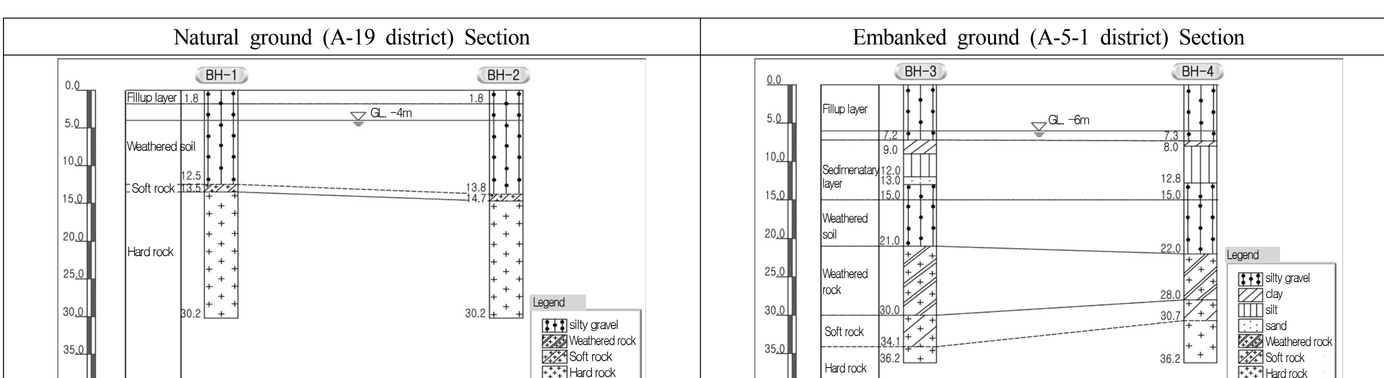



Fig. 2. Borehole Column Map at Each Investigation Position

and BH-2 (natural ground section), BH-3 and BH-4 (embankment ground section). The results of this investigation was utilized in determining ground layer formations and examining elastic waves in boreholes. To secure sufficient depth, the bore depths were 30.2m for BH-1, 2 and 36.2m for BH-3, 4. Table 2 and Figure 2 show the column map acquired using the core.

## 2.3 Results of Borehole Test

### 2.3.1 Result of Crosshole Test

Application of crosshole method follows the 3 steps as the following: acquisition of elastic wave signal through on-site test, acquisition of the information on elastic wave arrival time, and determination of elastic wave velocity at each depth and the column map (ASTM, 1996). Figure 3 is the overview of the on-site test using crosshole method. This method uses two or more boreholes for crosshole survey on elastic wave, and has to measure void and deviation of the boreholes. These requirements make this method more or less difficult to apply in actual tests, but the method produces much clearer signal, as there is no energy absorption by the surface layer.

Crosshole test on elastic wave was conducted on two positions within the site to measure S wave velocities at each depth of the ground. The bore depth of each boreholes were from 30.2 to 36.2m. Due to slime filling up the lower section of the casings, the depth actually measured was up to 28.5m for BH-1, 2 and 32m for BH-3, 4. We acquired data starting from the upper end of the holes and then moving downwards. Data was measured in 1-meter invervals in general. The distance between transmitter hole and receiver hole was 5m for both natural ground and embanked ground (Figure 1). We generated SV wave in vertical directions, and aquired a wave form with polarity characteristics.

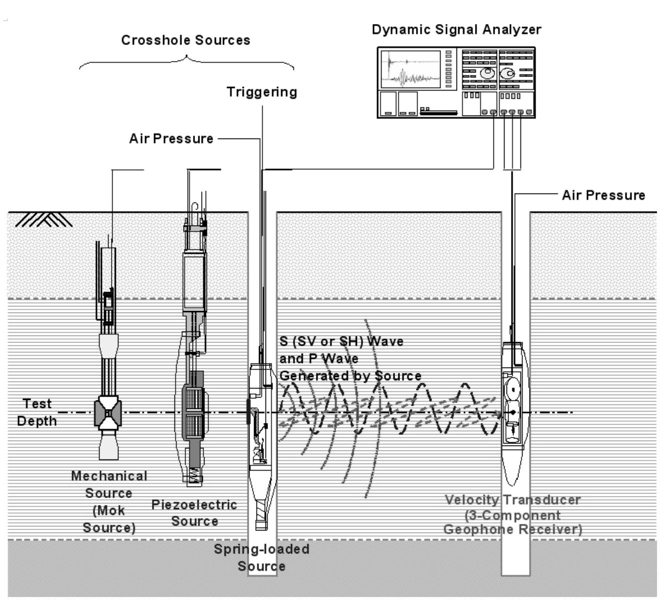
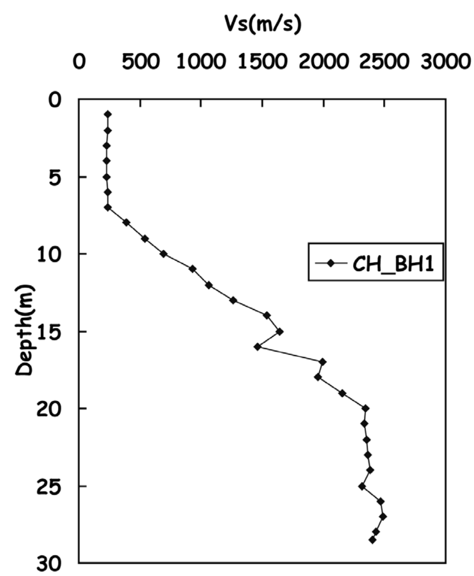


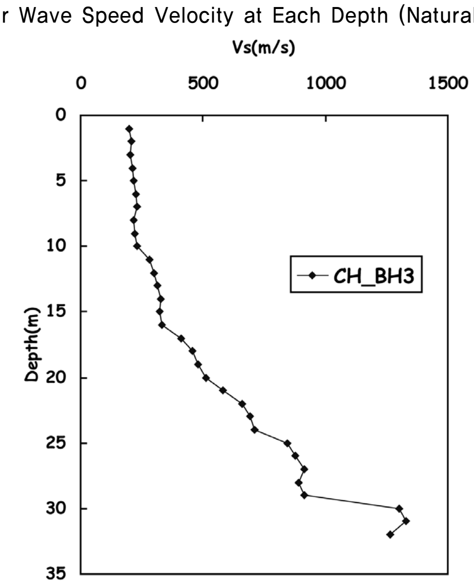

Fig. 3. Overview of Crosshole Test

Bore depth in natural ground section was 30.2m for both BH-1 and BH-2, and the ground water level was 4.0m; BH-1, the receiver hole, was installed with PVC casing, while BH-2, the receiver, was installed with steel casing up to the upper end of soft rock section. After completing boring, we found that the lower secion of casing was filled with slime. This allowed us to acquire data in up to 28.5m depth section. Bore depth in embanked ground section was 36.2m for both BH-3 and BH-4, and the ground water level was 6.0m; BH-3, the receiver hole, was installed with PVC casing, while BH-4, the receiver, was installed with steel casing up to the upper end of soft rock section. After completing boring, we found that the lower section of casing was filled with slime. This allowed us to acquire data in up to 32.0m depth section.

Figure 4 represents shear wave velocity at each depth of the




(a) Shear Wave Speed Velocity at Each Depth (Natural Ground)




(b) Shear Wave Velocity at Each Depth (Embanked Ground)

Fig. 4. Shear Wave Velocity at Each Depth (Crosshole Method)

ground within the investigated site. Shear wave velocity at each ground layer of natural ground (BH-1, 2) was: 235～240m/s at fillup layer, 225～1,067m/s at weathered soil layer, 1,263～1,536m/s at soft rock layer and 1,641～2,492m/s at hard rock layer. Tests on BH-3, 4 (embanked ground) showed the following shear wave velocity distribution: 199～229m/s at fillup layer, 217～323m/s at sedimentary layer, 333～583m/s at weathered soil layer, 659～1,302m/s at weathered rock layer and 1,263～1,329m/s at soft rock layer.

### 2.3.2 Result of Downhole Test

As can be seen in Figure 5, this method utilizes one borehole, and generates wave with ample compressed wave component by vertical strike on the plank installed at the surface with a sledgehammer, and generates wave with ample shear wave component by side strike. The elastic wave thus generated is acquired using the receiver installed in the borehole. In addition, elastic wave signals of compressed wave and shear wave at each depth are acquired through repeated measurement at all test depths (Kim et al., 2000; Crice, 2002; Kim, 2004).

For this test, the bore depth of BH-1 (natural ground) was 30.2m, ground water level was 4.0m, and PVC casings were installed. The distance between borehole and transmitter was 1.5m for P wave and 2.0m for S wave. The bore depth of BH-3 (embanked ground) was 36.2m, ground water level was 6.0m, and PVC casings were installed at each section. The distance between borehole and transmitter was 2.0m for P wave and 2.5m for S wave. Downhole method can be further classified into two methods: one method measures velocity at each test spacing in detail, and the other (Direct Method, DM) determines layer structure of the test site first, and then measures the average velocity at each layer. The first method includes Interval Method (IM), Modified Interval Method (MIM) and Refracted Ray Path Method (RRM). IM is relatively simple, producing test results without considering the velocity at upper layers. MIM considers the velocity at upper layers, but assumes straight path in its interpretation, while RRM considers the velocity at upper layers and assumes refracted ray path. As elastic waves are refracted when passing through layers with different rigidity in accordance with Snell's law, we have to apply interpretation method that considers refracted ray paths when conducting measurements using the downhole method (Kim et al., 2004). Therefore, this study classified grounds using Mean RRM suggested by Bang et al. (2006).

Figure 6 shows shear wave velocity at each depth measured using each method. Representative shear wave velocity at each ground layer of BH-1 (natural ground) was: 133m/s at fillup layer, 429m/s at sedimentary deposit layer, 1,263m/s at soft rock layer and 2,003m/s at hard rock layer. Tests on BH-3 (embanked ground) showed the following representative shear wave velocity

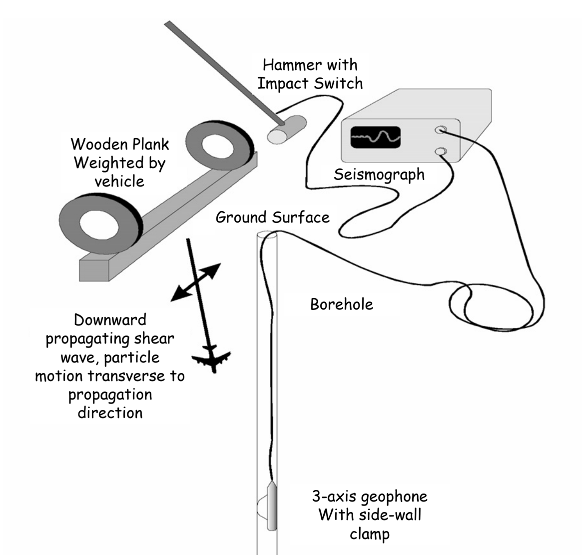
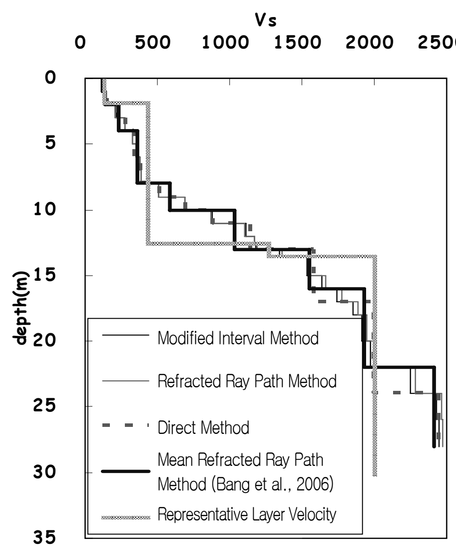
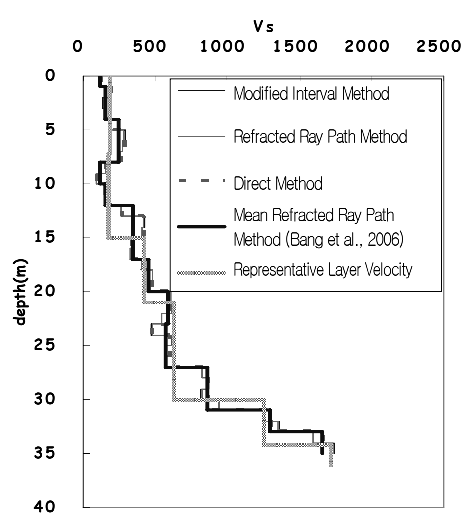



Fig. 5. Schematic of Downhole On-site Test (Crice, 2002)




(a) Shear Wave Speed Velocity at Each Depth (Natural Ground)




(b) Shear Wave Velocity at Each Depth (Embanked Ground)

Fig. 6. Shear Wave Velocity at Each Depth (Downhole Method)

at each layer: 184m/s at fillup layer, 171m/s at sedimentary layer, 419m/s at weathered soil layer, 624m/s at weathered rock layer, 1,254m/s at soft rock layer and 1,710m/s at hard rock layer.

### 2.3.3 Result of SPS Logging Test

SPS logging method measures elastic wave of ground using probes with sound source and receiver within boreholes. As indicated in Figure 7, the method calculates the velocity of P wave and S wave within each section by measuring time difference of the waves arriving at the two receivers. Using this non-compression method, P wave and S wave can be received without attaching the receivers to the hole walls. When the density around the receivers is almost the same as that of water density, the movement of the receivers are almost the same was that of the ground. By detecting water movements around the receivers with SPS logging method, the receivers can receive P wave and S wave in a non-compression way (GeoVision Geophysical Services, 2002). One advantage of SPS logging method is that it is effective for investigating grounds at depths unsuitable for downhole tests, as well as for deep sea investigation in which it is difficult to generate sound at surface level (GeoVision Geophysical Services, 2002).

For SPS logging, we conducted tests on two holes within the site to measure S wave velocity at each depth of the ground in the borehole, as shown in Table 3. As SPS logging method uses water within the hole as medium for energy emission, data measurement at upper part of ground water was not viable. Due to this limitation, we measured data starting from lower part of ground water, and then descending 1 meter each time. In BH-3, Table 3 shows that measurement section(5.0～32.0m) is higher than groundwater level (GL.-6m). This outcome can be explained by the fact that measurement of ground water level was conducted 5~7 days after boring was complete – when the ground water level must have become relatively stable – and logging was conducted the day after completion of boring, when means the ground water level was higher than the stable level.

Figure 8 shows shear wave velocity at each depth in the investigated area. Representative shear wave velocity at each ground layer of BH-1 was: 133m/s at sand layer, 499m/s at weathered soil layer, 1,453m/s at soft rock layer and 2,404m/s at hard rock layer. BH-3 (embanked ground) showed the following representative shear wave velocity at each layer: 175m/s at sand layer, 285m/s at sedimentary layer, 836m/s at weathered soil layer, 1,301m/s at weathered rock layer, and 1,684m/s at soft rock layer.

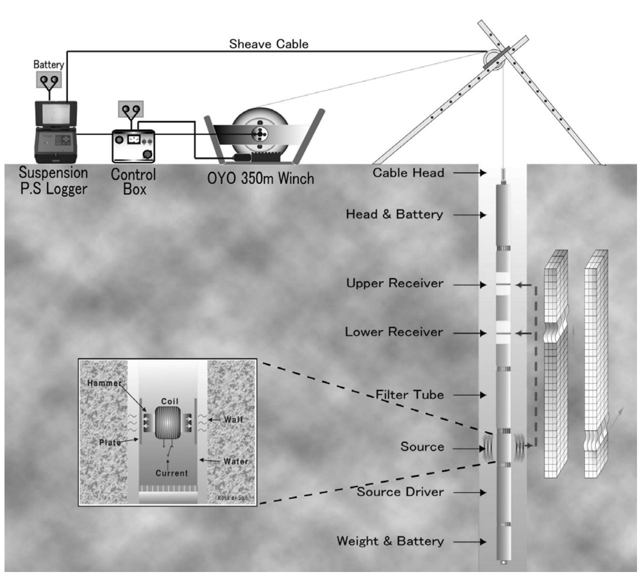
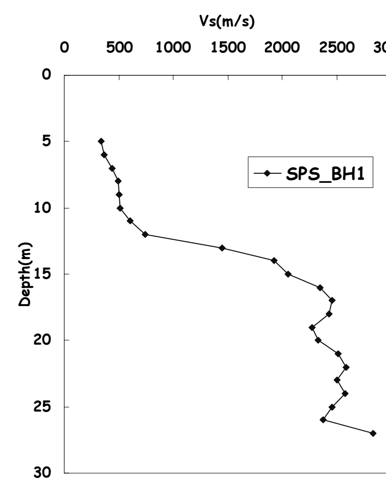


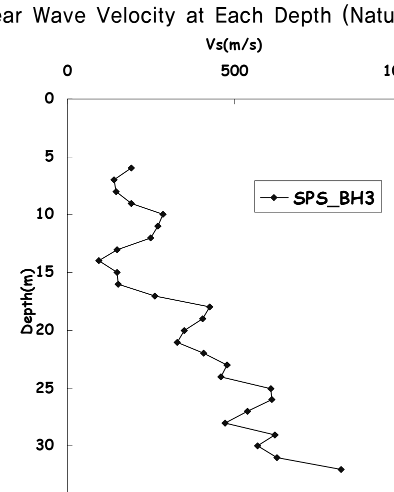

Fig. 7. Schematic of SPS Logging Overview (GeoVision Geophysical Services, 2002)

Table 3. SPS Logging Detail

| Hole No. | Bore Depth (GL.-m) | Measurement Section (m) | Ground Water Level (GL.-m) | Note |
|---|---|---|---|---|
| BH-1 | 30.2 | 5.0 ～ 27.0 | 4.0 | PVC Casing |
| BH-3 | 36.2 | 5.0 ～ 32.0 | 6.0 | PVC Casing |




(a) Shear Wave Velocity at Each Depth (Natural Ground)




(b) Shear Wave Velocity at Each Depth (Embanked Ground)

Fig. 8. Shear Wave Velocity at Each Depth (SPS Logging)

### 2.3.4 Result of SPT Uphole Test

SPT uphole method assumes horizontal layer structure within the tested area, just as downhole method does. On this assumption, the method generates 1-dimensional column map of shear wave velocity. The uphole method consists of the following stages: acquisition of elastic wave signals at each depth through on-site testing, acquisition of arrival time information and creation of shear wave veloicty column map, which is the method's final result. Figure 9 represents an overview of on-site Standard Penetration Test (SPT), which utilizes energy generated by penetrating the sampler. The traditional uphole method, which uses firepowder as seismic source, is not popular these days, because of its inefficiency in measuring physical properties of the ground in detail, and the difficulty in data acquisition. To overcome these shortcomings, this study measured physical properties using the SPT uphole method, a method designed to generate column map of compressed wave and shear wave velocity in the ground with more efficiency(Bang et al., 2006a, 2006b).

SPT uphole tests for this study were conducted at BH-1 and BH-3. BH-2 was not included due to a problem with detector installation, and we installed a sideline to the opposite direction. The first detector was installed 6m apart from the bore position, and horizontal/vertical speed meters were installed with 3-meter spacings at 12 positions. For embanked ground, the sidelines were set up on both sides of the boring position, similar to those for surface wave test. The first detector was installed 3m away, horizontal/vertical speed meters were installed with 3-meter spacings in both directions at 12 locations. Detection positions with good signal quality were selected for each site to create 1-dimensional column map of shear wave velocity. Waves were generated using SPT penetration energy. To verify the exact strike position, we performed separate strikes after SPT at each depth. Penetration depth was measured for each strike, and the result was utilized in interpretation. The test spacing was 1m down to weathered rock layer, and three more tests were conducted in 2m invervals after rock mass layer.

Figure 10 represents shear wave velocity at each depth within

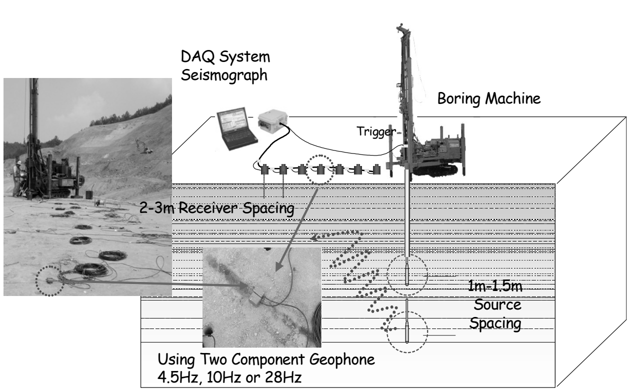
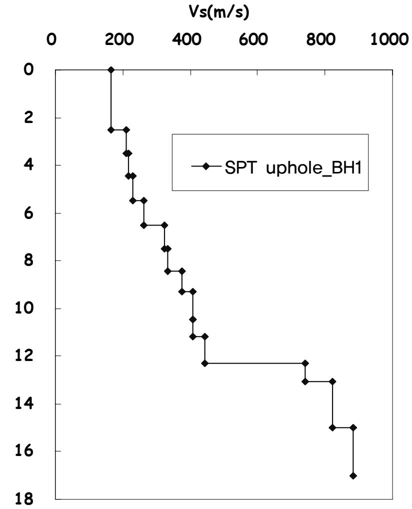
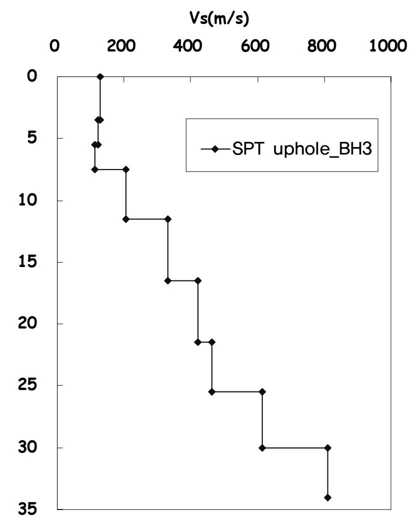



Fig. 9. Schematic of On-site Test using SPT Uphole Method




(a) Shear Wave Velocity at Each Depth (Natural Ground)




(b) Shear Wave Velocity at Each Depth (Embanked Ground)

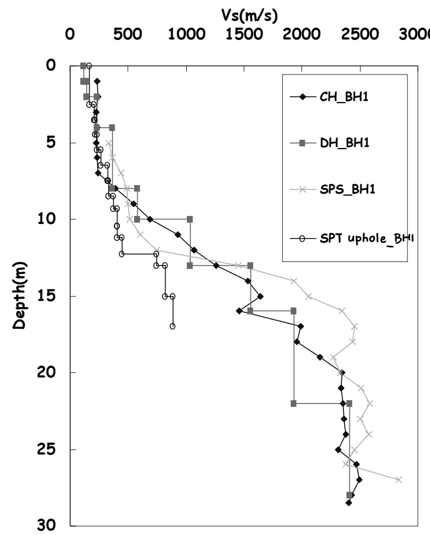
Fig. 10. Shear Wave Velocity at Each Depth (SPT uphole)

the tested area. Representative shear wave velocity at each ground layer of BH-1 was: 165m/s at fillup layer, 210~444m/s at weathered soil layer, 742m/s at soft rock layer and 823~883m/s at hard rock layer. BH-3 (embanked ground) showed the following representative shear wave velocity at each layer: 111~127m/s at fillup layer, 206~331m/s at sedimentary layer, 422m/s at weathered soil layer, 462~615m/s at weathered rock layer, and 810m/s at soft rock layer.

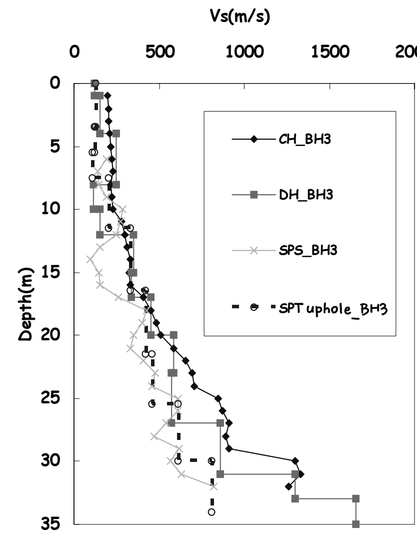
## 2.4 Comparison of Shear Wave Velocity Column Map and $V_{s,30}$ of Each Test Method

### 2.4.1 Shear wave velocity column map of each test method

Figure 11(a) summarizes the results of each test conducted in natural ground. Eac result was similar to each other in general, except for SPT uphole result in rock mass area where the SPT uphole test was not conducted. Figure 11(b) is a description of




(a) Shear Wave Velocity at Each Depth (Natural Ground)




(b) Shear Wave Velocity at Each Depth (Embanked Ground)

Fig. 11. Column Map of Shear Wave Velocity at Each Depth (all methods)

Table 4. $V_{s,30}$ and Ground Classification for Each Method (Natural Ground, BH-1)

| Test Method | | $V_s$ Column Map End Depth (layer name) | $V_{s,30}$ (m/s) | Site Classification |
|---|---|---|---|---|
| Borehole Test | Crosshole | 28.5m (hard rock) | 641.08 | $S_C$ |
| | Downhole | 28m (hard rock) | 601.52 | $S_C$ |
| | SPT-uphole | 17m (hard rock) | 439.40 | $S_C$ |
| | SPS-logging | 27m (hard rock) | 821.26 | $S_B$ |

Boring Column Map : Fillup Layer (0~1.8m), Weathered Soil (1.8~12.5m), Soft Rock (12.5~13.5m), Hard Rock (13.5~30.2m)

each test conducted in embanked ground. Each method showed similar results in fillup, sedimentary and weathered soil layers (~21m), as well as in weathered rock layers. These results verify the reliability of the above results. As can be seen in Figure 11(b), the tests produced similar results in general, except for SPS logging, which produced small values in some soil layers.

### 2.4.2 Comparison of $V_{s,30}$ in natural ground

We determined the average shear wave velocity ($V_{s,30}$) in upper 30m area based on column map of shear wave velocity generated by each test method. $V_{s,30}$ was calculated using Equation (1), and ground types were determined in accordance with the site classification standard used in Korea. The result is expressed in Table 4.

$$V_{s,30} = 30 / \left( \sum_{i=1}^{n} \frac{d_i}{V_{si}} \right) \tag{1}$$

where $d_i$ represents the thickness(m) of $i$th layer within the 30-meter ground, and $V_{si}$ represents the shear wave velocity(m/s) at $i$th layer.

To verify the appropriateness of ground interval in downhole method, $V_{s,30}$ was calculated using the shear wave velocity measured in small spacings (refracted ray path method), the shear wave velocity measured in sections divided in cosideration of measurement error and inclination of acquired signals (mean refracted ray path method) and the shear wave velocity in each section based on boring column map. As expressed in Table 5, the result produced with shear wave velocity measured with small spacings was smaller than the result produced with representative shear wave velocity at each layer by approximately 63m/s. Even though they were classified as the same $S_C$ grounds based on the classification standard, the difference is expected to increase in case of a ground with deeper soil layer. Therefore, for reasonable seismic interpretation, the shear wave velocity needs to be calculated in detail for each depth.

As for SPS logging, the shear wave velocity could not be measured as the test could not be conducted in upper 5 meters due to ground water level. Therefore, $V_{s,30}$ was calculated by expadnding the shear wave velocity measured at the highest part possible to the surface. Comparison of $V_{s,30}$ of each test method

Table 5. Ground Classification based on Ground Layer Thickness (Natural Ground, BH-1)

| Classification | Refracted Ray Path Method | Mean Refracted Ray Path Method | Representative Velocity at Each Layer |
|---|---|---|---|
| $V_{s,30}$ (ground classification) | 571m/s ($S_C$) | 601m/s ($S_C$) | 634m/s ($S_C$) |

Table 6. $V_{s,30}$ and Ground Classification for Each Method (Embanked Ground, BH-3)

| Test Method | | $V_s$ Column Map End Depth (layer name) | $V_{s,30}$ (m/s) | Site Classification |
|---|---|---|---|---|
| BoreholeTest | Crosshole | 32m (Soft Rock) | 346.16 | $S_D$ |
| | Downhole | 35m (Lower Soft Rock) | 269.33 | $S_D$ |
| | SPT-uphole | 34m (Soft Rock) | 241.73 | $S_D$ |
| | SPS-logging | 35m (Soft Rock) | 241.91 | $S_D$ |
| Boring Column Map : Fillup Layer (0～7.2m), Sedimentary Deposit (7.2～15m), Weathered Soil (15～21m), Soft Rock (21～30m), Hard Rock (30～34.1m) | | | | |

showed that the velocity at hard rock layer measured with SPT uphole method was 880m/s, much lower than other methods. This difference can be explained by the fact that the test site has a relatively deep hard rock layer. On the contrary, SPS logging method was the only one classified as $S_B$ ground, as the shear wave velocity at the ground layer in upper ground water level could not be measured and assumed to be relatively high, and the velocity at upper hard rock layer was evaluated to be relatively high. As for the other methods, $V_{s,30}$ measurement showed similar results at 500m/s~600m/s, and they were all classified as Sc ground, which signifies that the acquired result was reliable.

### 2.4.3 Comparison of $V_{s,30}$ in embanked ground

We determined the average shear wave velocity ($V_{s,30}$) in upper 30m area based on column map of shear wave velocity generated by each test method. $V_{s,30}$ was calculated in the same way as in natural ground (A-19 district), and ground types were determined in accordance with the site classification standard used in Korea, as expressed in Table 6.

As for SPS logging, the shear wave velocity could not be measured as the test could not be conducted in upper 6 meters due to ground water level. Therefore, $V_{s,30}$ was calculated by expadnding the shear wave velocity measured at the highest part possible to the surace. Comparison of $V_{s,30}$ of each test method showed that the shear wave velocity measured with crosshole method was similar to those of other methods up to the weathered soil layer, but the velocity at weathered rock layer was evaluated to be higher than those of other methods, resulting in relatively higher $V_{s,30}$. In general, however, $V_{s,30}$ was evaluated to be similar across all test methods, and the site classification was also similar ($S_D$). As the test site was influenced by non-compressed fillup layer in the upper area, $V_{s,30}$ was evaluated to be lower than in the natural grounds discussed above. This goes on to show that measurement of shear wave velocity in the upper area is crucial in determining $V_{s,30}$.

## 3. Conclusions

In this study, we conducted various elastic wave tests using various boreholes in Natural/embanked grounds. In particular, we measured shear wave velocity to be used in seismic design, and compared the characteristics and accuracy of each test method. The findings of this study can be summarized as the following.

1. The shear wave velocity measured with each test method in this study was quite similar to each other. Measurement results at soil layer showed very low distribution, which signifies that the results produced with each method was very much reliable.
2. The downhole method produced very similar results as the crosshole test method, which is known for its accuracy. But measurement of shear wave velocity using mean refracted ray path method showed lower value than the values produced by measurement using representative velocity at each layer. Even though they were classified as the same $S_C$ grounds based on the classification standard, the difference is expected to increase in case of a ground with deeper soil layer. Therefore, in order to conduct reasonable seismic interpretation, the shear wave velocity needs to be measured in as small invervals as possible at each depth.
3. SPS logging showed reliable results in the case of no casing, i.e. in the rock mass. In SPS logging method, acquisition of the arrival time of shear wave can be problematic when the casing is placed within soil layers, where the shear wave velocity is low. To avoid this problem, the test should be conducted without casing after reinforcing hole walls with such materials as bentonite. In case of using casings, the initial information should be carefully selected.
4. As for SPS logging method, generating the input data for seismic interpretation can be problematic, as the physical properties of upper ground water level cannot be measured. To avoid this problem, the column map of shear wave velocity for

all areas should be acquired by conducting additional tests using such methods as surface wave method. The shear wave velocity was determined at a relatively higher value, as the SPS logging method applied in this study could not verify the shear wave velocity at the soil layer in the upper ground water level. And the shear wave velocity at upper hard rock layer was evaluated to be high. Therefore, this method was classified as $S_B$ ground unlike other methods.

5. The SPT uphole method produced similar results at soil layers and upper rock mass layers. But the test result was not reliable as SPT sampler penetration was not conducted during rock mass boring. As this method conducts measurement and boring simultaneously, however, it offers the advantage of avoiding various problems caused by borehole casing installation, thereby reducing the overall test time.

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