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A Pilot Study of In-hole Seismic Method

인홀탄성파시험의 타당성 연구

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요 지

지난 반세기 동안 검측공 탄성파시험은 시험 장비 및 그 배치에 따라 크로스홀, 다운홀, 서스펜션로깅과 같은 시험으로 발전하였다. 이런 현장시험은 장비와 시험기법이 꾸준히 개선되어 지반 및 지진공학 분야의 부지특성규명에 매우 값진 기술이 되었다. 그러나 이 기술은, 공학적 의의와 중요성에도 불구하고, 표준관입시험처럼 실무에 보편적으로 적용되지 못하고 있다. 그 이유는 장비가 복잡 정교할 뿐만 아니라, 사용하기 어렵고 비싸기 때문이다. 이 연구에서는 경제적이고 실용적인 지반의 동적물성치 계측 기술 개발을 목표로 하여 인홀시험법을 연구하였다. 이 연구에서 개발한 인홀장비 시작품은 NX 크기의 검측공에 사용하고 맨손으로 다룰 정도로 작고 가볍다. 이 장비의 발진장치는 여러 현장에서 크로스홀시험을 통하여 그 성능을 검증하였고 꾸준히 개선되고 있다. 세 현장에서 인홀시험을 수행하고 그 결과를 크로스홀시험 결과와 비교하여 타당성을 검증하였다.

Abstract

Over the past half century, borehole seismic surveys have been diversified into the three techniques such as crosshole, downhole, and suspension logging according to their devices and testing configurations. These field techniques have been improved, in terms of equipment and testing procedures, and are very valuable in the evaluation of ground characteristics for geotechnical and earthquake engineering problems. Yet, despite the importance and significance of the techniques as engineering tools, the techniques are not much used as standard penetration test (SPT) by practicing engineers. The possible explanations are cost and operational difficulties of the surveys as well as sophistication and complexity of the devices. An in-hole seismic method has been developed to meet the requirement of economical testing cost and practicality in engineering practice to measure dynamic soil properties. The prototype in-hole probe developed herein is small and light enough to be fit in three-inch boreholes and to be handled with bare hands. The performance of the source has been evaluated through extensive crosshole tests at various sites. The in-hole seismic method was adopted at three test sites and verified by comparing with crosshole results.

Keywords : In-hole method, Prototype in-hole probe, Shear wave velocities

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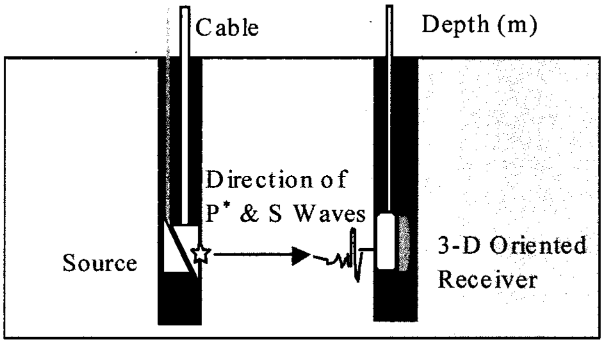
1. Introduction

1.1 Present Borehole Methods

1.1.1 Crosshole Method

The crosshole seismic method is a very accurate and detailed profiling method (Mok 1987, Stokoe and Hoar 1978, Stokoe and Woods 1972, Wilson et al 1978, Woods and Stokoe, 1985) that has been used in geotechnical engineering for 30 years. In the field procedure, the times required for body waves to travel horizontally between two or more points located at the same depth are measured (see Figure 1). By moving the source and receivers down the boreholes in unison, it is possible to generate accurate and detailed profiles of compression (P) and shear (S) wave velocities from which the respective soil moduli (soil stiffness) are calculated. However, the test is expensive because two or more boreholes have to be drilled, cased and inclinated. Moreover, the requirement of intimate bonding between the casing and surrounding soil for successful testing involves extra troublesome grouting work and researchers, as well as practicing engineers, are sometimes reluctant to use the technique.



*P = compression waves
S = shear waves

Fig. 1. Crosshole seismic test with two boreholes

1.1.2 Downhole Method

The downhole seismic method involves a test that is less expensive and simpler to perform in the field than the crosshole test. Furthermore, it is simpler to analyze the field data. Testing is conducted with a heavily-loaded plank source on the ground surface and receivers placed at various depths in one borehole (as illustrated in Figure 2). The source is transiently excited and stress wave travel times are measured over inclined ray paths between the source and receivers at depth. Because the energy source is offset horizontally from the collar of the borehole, the travel times are adjusted at shallow depths for this offset. The adjustment is intended to convert the actual travel times along the slant paths from the source to the receivers into the equivalent times required to travel vertically from the ground surface to the receivers. The method results in rather smooth velocity profiles, especially when compared with the more detailed profiles determined by the crosshole method (Mok, 1987). Also,

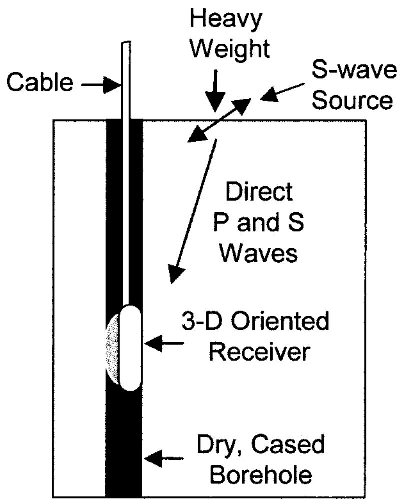


Fig. 2. Downhole seismic test

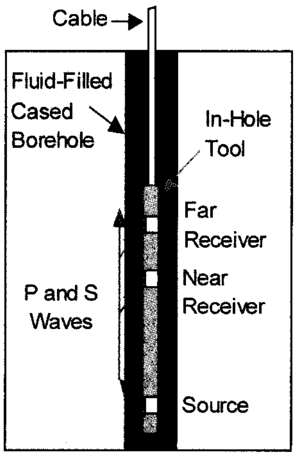


Fig. 3. Suspension logging

as the measurement depth increases, the resolution and data quality decrease because the ray paths are becoming longer and longer.

1.1.3 Suspension Logger

The third type of borehole seismic test is the suspension logger (Nigbor and Imai 1994). This technique is the most recent addition to the suite of borehole methods, having become available and accepted in the U.S. in the past two decades. The suspension logging system is shown schematically in Figure 3 and includes an in-hole tool, consisting of an energy source, isolation tubes and two biaxial geophone receivers. The energy source is a solenoid whose activation causes a "hammer" to strike the tool casing, producing an impulsive pressure wave in the fluid-filled borehole. This pressure wave transmits energy to the borehole wall, producing both P and S waves that travel through the geologic formation. The distance from the energy source to the near receiver is often approximately 2 to 3 m. The distance between receivers is about 1 m. The total length of the tool is approximately 7 m, with the center point between the two receivers approximately 3 to 4 m above the bottom of the tool.

An examplary waveform record measured in suspension logging is shown in Figure 4 (Stokoe et. al. 2003). The patterns of the shear (S) wave arrivals are generally not sharp breaks due to noise interference. The travel time to the peak of the first S-wave cycle is then picked because this point can usually be identified more accurately than the first break due to interference from the P wave and other noise. The results of suspension surveys are usually presented as plots of interval velocities versus depth. The velocity across the interval between the two receivers is calculated by dividing the fixed distance between the receivers (about 1 m) by the difference in travel times from the source to the respective receivers; hence, an interval travel time. In alluvium at Yucca mountain (Stokoe et. al. 2003), this procedure could not be adopted due to a general lack of sufficient signal strength at the far receiver (although Figure 4 shows a good interval S-wave measurement with a time of Dts at the depth shown). This loss of signal was attributed to the high attenuation in the compression P- and S-wave signals at the site. Therefore, velocities based on the source-to-near-receiver measurements were the only ones calculated. The S-wave energy was identified at the near receiver as described above, and the initial arrival was estimated in the waveform as illustrated in Figure 4. At shallow depths (less than 10 m), even this procedure was of no use because of the poor data quality and the S- and P- velocity profiles could not be resolved as shown in Figure 5.

It is important to note in Figure 5 that only two of

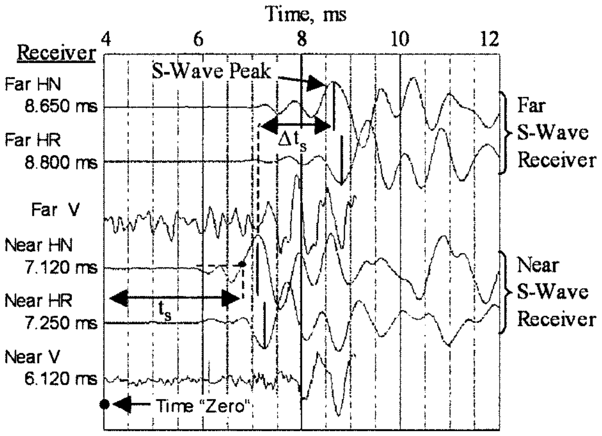


Fig. 4. Suspension log at one measurement depth (Stokoe et. al. 2003)

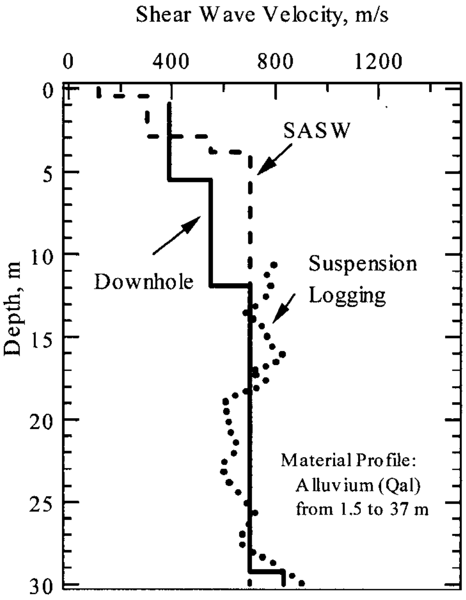


Fig. 5. Shear wave velocity profiles measured with three different seismic methods (Stokoe et. al. 2003)

the three borehole methods discussed herein were used at this site (no crosshole testing was performed). The third method shown in the figure is a noninvasive surface wave method which requires no boreholes. This method is called spectral-analysis-of-surface-waves (SASW) testing and was not discussed in this background review because it does not involve boreholes. SASW testing represents a global measurement whereas the in-hole probe proposed herein is a localized measurement with excellent resolving powers at depth (at least in theory... but we are confident that this will be true).

1.2 In-hole Method Proposed

The basic concepts behind the in-hole probe are illustrated in Figure 6. The probe is similar to the suspension logging tool except for four key features. First, the source and receiver components of the probe are in intimate contact with the borehole wall (if the borehole is uncased) or with the borehole casing. Therefore, the borehole does not have to be filled with fluid (as needed by the suspension logger) and more energy can be delivered to the geologic material. Either air bags or spring devices will be used to couple the source and receivers to the borehole. Second, the isolator rod consists of stacks of sliding discs with significant acoustic-impedance contrasts between adjacent discs. Sliding motion and impedance differences between the discs will be used to absorb and disperse wave energy transmitted by the rods so that it will not interfere the wave propagating through the geologic material surrounding the borehole. Excellent shear and compression wave signals should be measured so that determination of travel times and calculation of wave velocities and material stiffnesses can be automated. This automation is a third difference between the proposed probe and the existing suspension logger. The fourth difference is that the probe will be modularized and combined according to the testing conditions and applications. The overall length of the shortest version of the probe including one source and two receivers will be about 2 m.

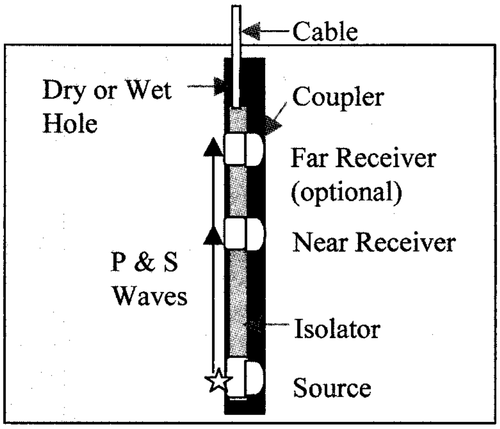


Fig. 6. Conceptional diagram of in-hole seismic tests

The existing suspension logger is quite substantial and very expensive. Due to the expense of the tool, there is only one commercial company that offers testing services with the tool. The proposed probe would be much less expensive, easier to deploy, and automated. As shown in the comparisons in Figure 5, the suspension logger often does not perform well at depths of 6 to 10 m from the ground surface. In addition, the logger does not work well near the bottom of the borehole. The proposed probe should overcome these shortcomings.

2. Development of the In-hole Source

2.1 Borehole Seismic Sources

Three types of borehole seismic sources have been developed and successfully used in crosshole testing in geotechnical engineering applications. These source types are mechanical, solenoids and piezoelectric discs (Mok et.al. 1999, Mok et.al. 2001, Roblee 1991, and Roblee et.al. 1994). These sources offer insight into the development of the in-hole probe source. The mechanical source consists of a wedging mechanism actuated by a double-acting air cylinder and a pair of impact weights. This source has been used at numerous sites and has proven to be an excellent seismic source in the crosshole test. Solenoid-type sources have employed rather large solenoids successfully. The piezoelectric source utilizes the behavior of piezoelectric materials, which change physical dimensions when subjected to an electric field (Paik et. al. 1997). The stacks of piezoelectric discs are charged with an electric power, resulting in a stored distortion. Once fully charged, the electric field is quickly dissipated by shorting with a triggering signal, thereby rapidly releasing the stored strain energy in a transient seismic pulse. Two major features are good control and repeatability of the generated seismic signal. The primary drawbacks of the source are the complexity and cost. The co-principal investigators of the proposed research have developed all three types of sources for their use. The mechanical mechanism is physically too large to be integrated into the in-hole probe. The solenoid sources need to be reduced in size but represent a feasible device. The piezoelectric ones are not appropriate for generating seismic waves in soil, and they require an elaborate electric device and electric power. Thus, the solenoid mechanism is the source of choice for the in-hole probe.

A spring-loaded source has been considered and a prototype was developed for use in a borehole. Its implementation has proven the source to be excellent but cumbersome to use in its present form because it is manually operated. However, it forms the basic idea, combined with a solenoid driver to replace the manual action for the in-hole source, so a brief description of this mechanism follows.

2.2 Prototype Source For In-hole Method

The depictive description of the prototype source is shown in Figure 7. By manually pulling the trigger-cable at the ground surface, a trigger-arm releases a loaded impact-pestle in the source, thereby impacting the borehole wall. Simultaneously, the impact-pestle is reloaded by a return spring. The inflation of an air bag ensures intimate contact between the source and borehole wall and enhances the amount of the impact energy transmitted to the geologic material. The key features of the source include simplicity and ruggedness of the device, sufficient energy for use in soil, and no electric power source needed for operation. Figure 8 shows pictures of the prototype version that was used in research.

3. Performance of the In-hole Source

To evaluate the performance of the source, extensive crosshole tests were performed at various sites including a test site at Kyung Hee University, Juk-jeon apartments site, and several benchmark sites for earthquake research at HaeMi-, SaCheon- and TongYoung-city in Korea (Kang 2003, Kim 2002, Mok et. al. 2002, Mok et.al. 2003). Typical compression and shear wave signals are shown in Figure 9. For P-wave measurements, source and receiver were oriented to face each other. The first big trough of the signal is the first arrival of P-wave (designated with "P" in the upper figure of Figure 9). In shear measurements, source and receiver were

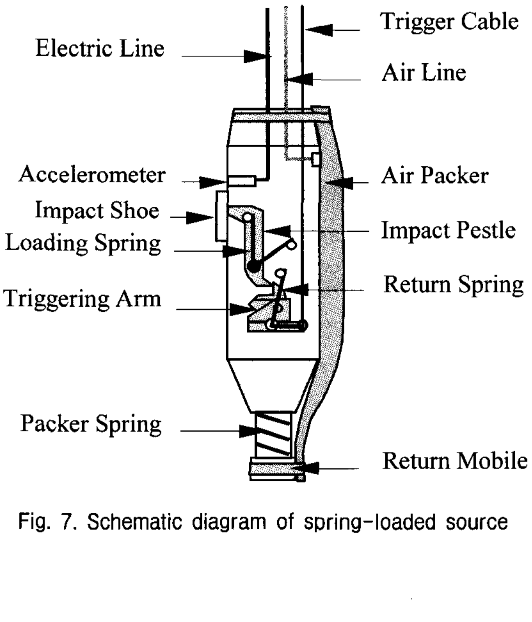


Fig. 7. Schematic diagram of spring-loaded source

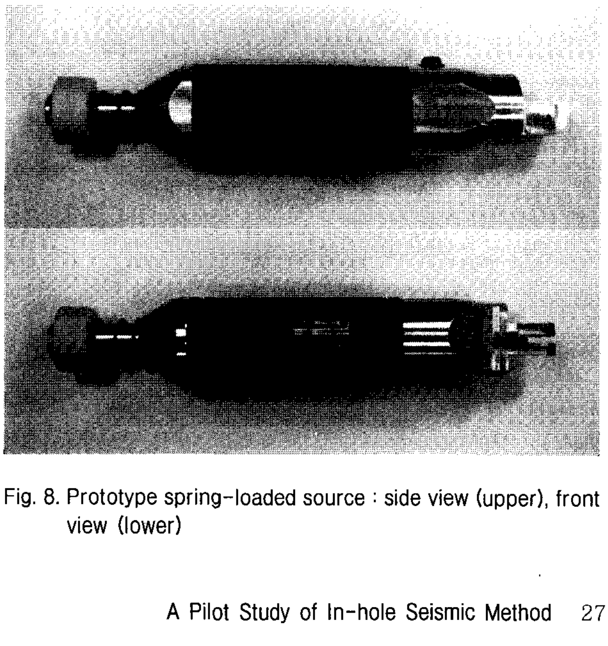


Fig. 8. Prototype spring-loaded source : side view (upper), front view (lower)

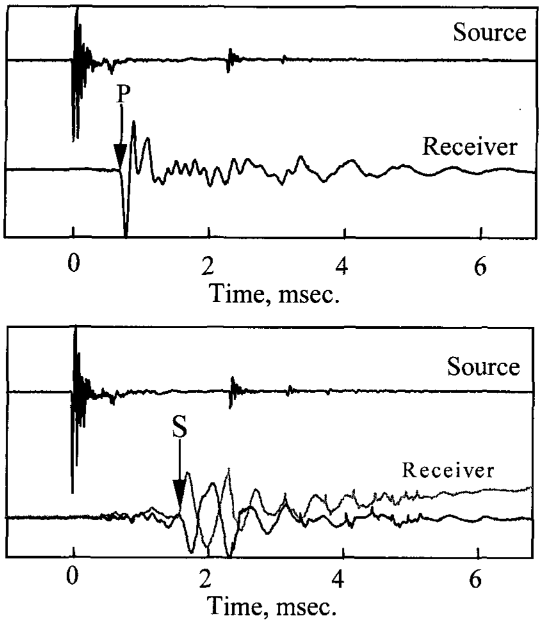


Fig. 9. Typical P-wave and S-wave crosshole signals generated with the manual version of the prototype source

placed perpendicular to the ray path. The first big surges, that are reversed each other in the pair of signals generated by source impacts in opposite directions (forming "butterfly" pattern; designated with "S" in the lower figure) are the first arrivals of the shear wave energy. The records show identifiable P- and S-wave patterns, thus the first arrival time can be easily picked. The source has been proven to generate excellent P- and S-wave energy and the records shown in Figure 9 are readily usable in the automation portion in future study.

4. Pilot In-hole Testing

To evaluate the feasibility of the in-hole method, a temporary in-hole probe was assembled with the prototype source, one 3-D receiver (Mark Products, 4-Hz geophones), and a flexible rubber hose as an isolator as shown in Figure 10. The recording system used in all testing is HP35670A dynamic signal analyzer. The right side device was the prototype source and was connected to the receiver(left side) with a piece of water hose. The distance between impacting and monitoring points was 1 meter. At Sumjin-Dam site, the probe was lowered by 15 meters in a 7.5-cm diameter uncased borehole and shear wave measurements were carried out at every 0.5 meters to the depth of 15 meters (Kang 2003, Kim 2002). In the rock layer, distinct shear waves were measured because the stiffness of rock is higher than that of the connecting hose as shown in Figures 11 and 12 because the stiffness of the rock was higher than that of the connecting hose. The typical shear wave signal shown in Figure 11 is distinctive enough to pick up the first arrival

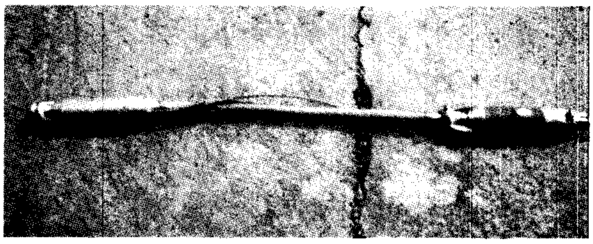


Fig. 10. Prototype version of a simplified in-hole probe

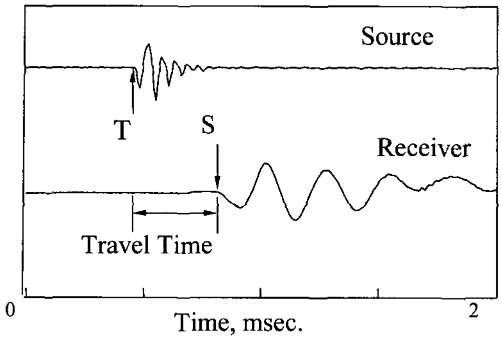


Fig. 11. Shear wave signal from prototype in-hole probe shown in figure 10

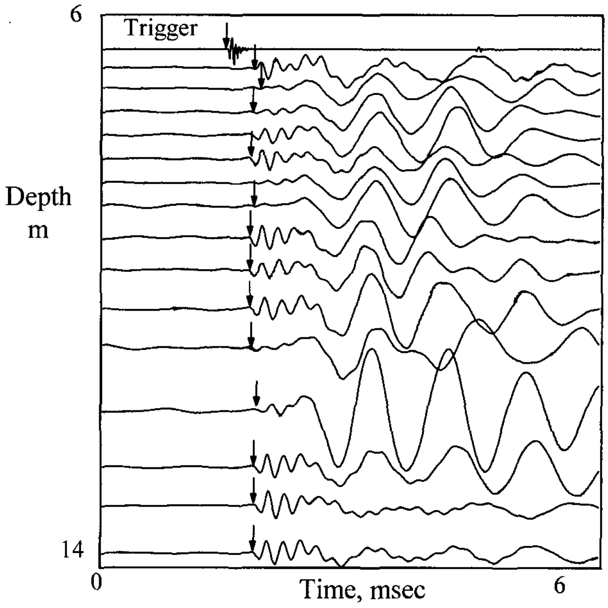


Fig. 12. Shear wave signals from in-hole tests

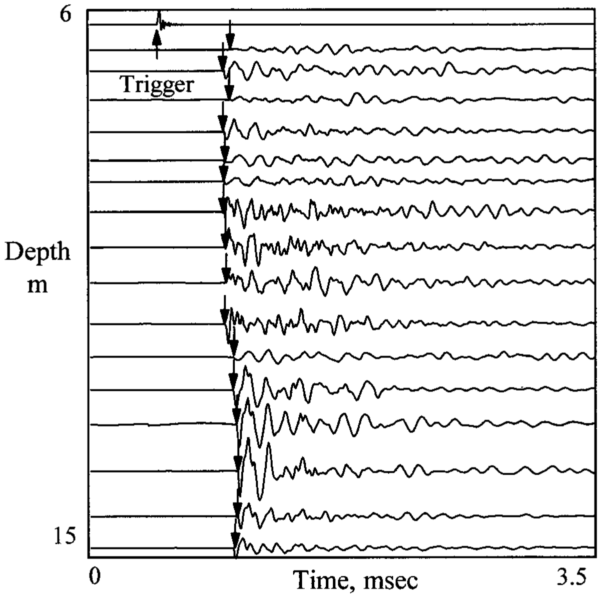


Fig. 13. Shear wave signals of crosshole tests

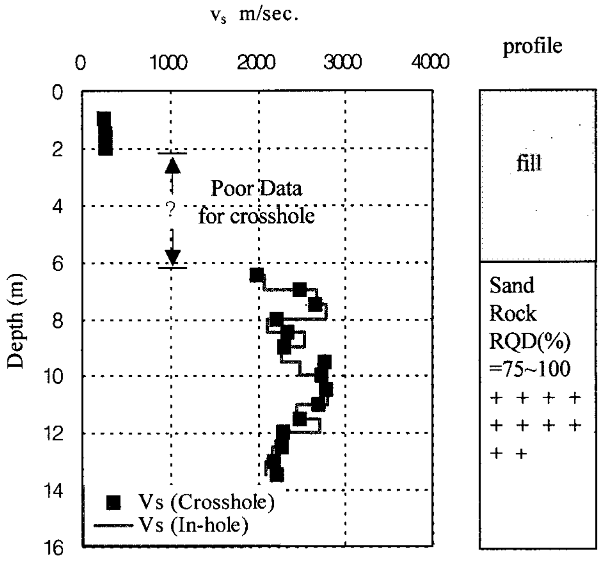


Fig. 14. Comparison of shear wave velocity (VS) profiles determined with the prototype in-hole probe and traditional crosshole tests

of shear energy (denoted by "S"). The predominant frequency and wave length of shear waves are the order of 4kHz and 0.5m, respectively. Hence, the shear wave seems to sample as deep as one wave length (0.5m) behind the borehole wall. In the top-soil layer, the noise transmitted through the connecting hose interfered the wave propagated through the ground, indicating an improved type of "isolation rod" was needed for measurements in soil. Another borehole was drilled by 2.1 meter (7 ft) apart from the original borehole to conduct crosshole testing. The prototype source and the same receiver were used, and the measured S waves are shown in Figure 13. The sharp breaks of the shear waves are so obvious that automated processing of the waveforms can readily be achieved. Comparison of the average shear wave velocity profiles from companion tests with the prototype tests is presented in Figure 14 and shows good agreement. The difference in the velocity profiles could be attributed to the anisotropy of the rock formation. The rock mass appeared to be fissured and cracked horizontally. Shear waves of crosshole testing sampled horizontally through the solid part of the rock mass and hence traveled faster than those of in-hole testing. On the other hand, shear wave of in-hole testing had to cross the horizontal fissures and traveled slowly. The result of in-hole testing seems more sensible in seismic design, because the pattern of shear wave traveling of in-hole testing is more similar to the upward propagation of earthquake shaking than crosshole.

To examine how the prototype source performs in soil, the source and receiver were lowered separately without connecting each other in the hand-augured borehole at KHS(Kyung Hee University) site and Juk-Jeon site. The shear waves shown in Fig. 15 indicate that the proposed in-hole probe will work well, if the isolation is improved. By drilling another borehole for source, crosshole tests were performed to verify the in-hole test results. Two

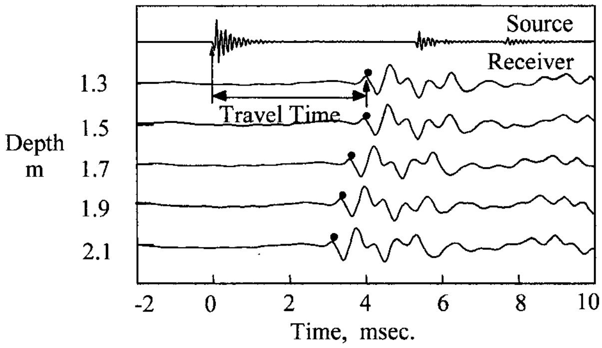


Fig. 15. Shear waves measured in soil layer at KHU site

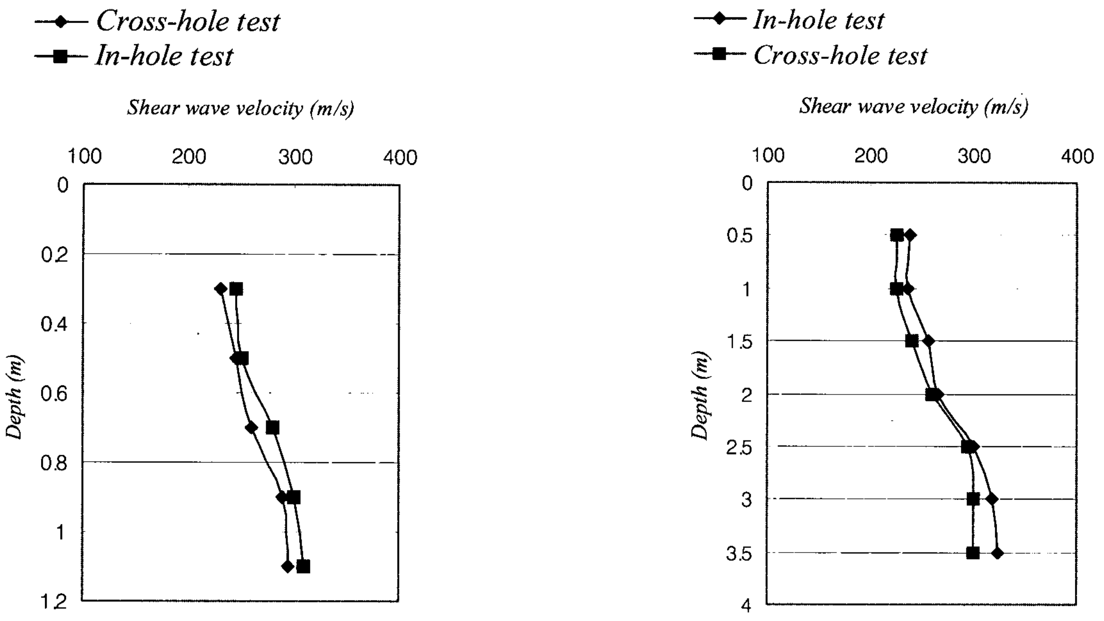


Fig. 16. Shear wave velocity profiles at KHS (left) and Juk-Jeon(right)

measurements agree well in the range of shear wave velocity of 230 m/sec. to 300 m/sec as shown in Figure 16. The predominant frequency and wave length are about 1 kHz and 0.2-0.3m, respectively. The shear waves seemed to sample as deep as one wave length (0.2-0.3m) behind the borehole wall.

5. Conclusion

In-hole seismic method has been developed to be used practically by geotechnical engineers in the areas of measuring dynamic subsurface material properties for earthquake-resistant designs. The prototype probe and testing technique adopting three sites have been proven to perform reasonably well in comparison with crosshole test results. This prototype source will be further refined and integrated into the in-hole probe to meet the requirements of economy and practicality. A special isolator should be developed with the concept of absorbing and dispersing the noise by the action of sliding and solving the differences of acoustic impedance of adjacent discs.

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