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IN-HOLE SEISMIC METHOD FOR DYNAMIC STIFFNESS MEASUREMENTS OF GEOMATERIALS

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ABSTRACT

In-hole seismic method has been developed to measure dynamic properties of subsurface materials for earthquake-resistant designs. The most updated version of in-hole probe is small and light enough to be fit in three-inch boreholes with several functional improvements including an electric triggering device and two mechanical packers operated by servo-motors. The performance of the source has been evaluated through extensive crosshole tests at various sites. The in-hole seismic method has been adopted at various sites and verified by comparing with crosshole results.

Keywords: In-hole Seismic Method, In-hole Probe, Shear Wave Velocities

INTRODUCTION

Over the past half century, borehole seismic survey has been diversified into the three techniques such as crosshole, downhole, and suspension logging test 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 earthquake engineering problems. Yet, despite the importance and significance of the techniques as engineering tools, the techniques are not as much used as standard penetration test (SPT) by practicing engineers. It is partly because the century-old SPT becomes a workhorse of strength evaluation even though it involves several decisive weaknesses such as the different shearing mechanism between dynamic punching and static failure, variations of energy delivered, etc. In the other hand, seismic techniques are presently used in evaluating dynamic stiffness and are seldom extended their usage in correlating with strength due to the cost and technical complexity. An in-hole seismic method has been developed to meet the requirement of economic testing cost and practicality in engineering practice to measure dynamic soil properties. The three borehole tests and the in-hole method are briefly described herein.

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) that has been used in geotechnical engineering for the past 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 for their verticality. Moreover, the requirement of intimate

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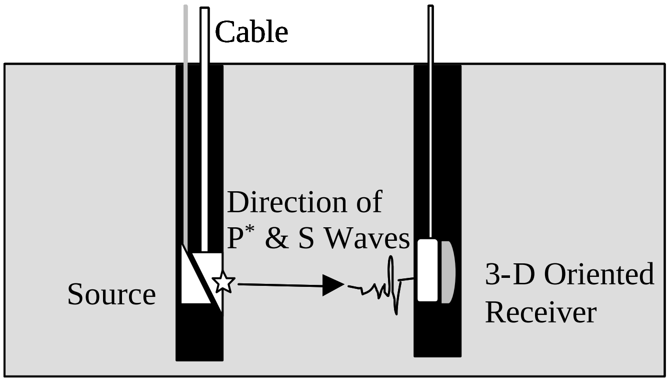
bonding between the casing and surrounding soil for successful testing involves extra troublesome grouting work and researchers, as well as practicing engineers, are sometimes reluctant to use the technique. The technique gives detailed stiffness profiles but often cannot detect thin slow strata sandwiched between two hard layers.



P* = compression waves
S = shear waves

Figure 1. Crosshole Seismic Test with Two Boreholes

Downhole Method

The downhole seismic method involves a test that is a 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 to 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, as the measurement depth increases, the resolution and data quality decrease because the ray paths are becoming longer and longer.

Suspension Logging

The third type of borehole seismic test is the suspension logging (Nigbor and Imai, 1994). This technique is the most recent addition to the suite of borehole methods, having become available 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.

Tow drawbacks of the method are that it generally can not be performed in a steel or thick plastic casing if soft soils are to be tested and it does not work well within 7 m of the ground surface (Stokoe et al., 2003).

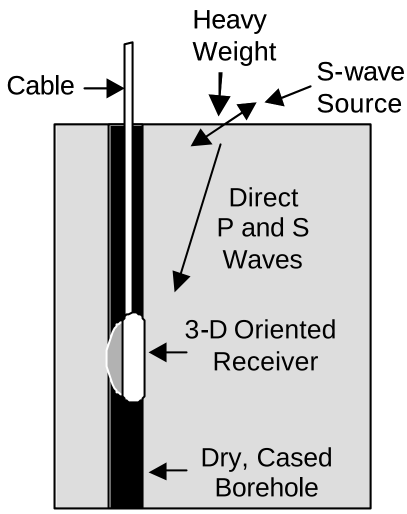


Figure 2. Downhole Seismic Test

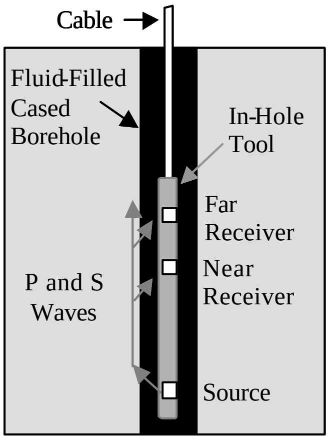


Figure 3. Suspension Logging

In-hole Method Proposed

The basic concepts behind the in-hole probe are illustrated in Figure 4. The probe is similar to the suspension logging tool except for two key features. First, the source and receiver components of the probe are in intimate contact with the borehole wall. Therefore, the borehole does not have to be filled with fluid (as needed by the suspension logging) 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. The second difference is that the probe is modularized and combined according to the testing conditions and applications. The overall length of the probe including one source and one receiver is be about 1.5 m.

The existing suspension logging 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.

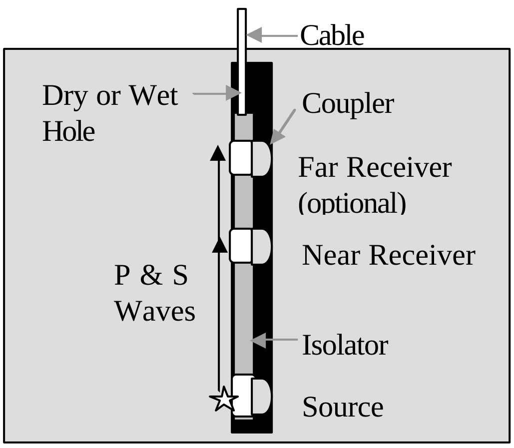


Figure 4. Conceptional Diagram of In-hole Seismic Tests

DEVELOPMENT OF IN-HOLE SOURCE

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, 1990; 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 mechanical mechanism is physically too large to be integrated into the in-hole probe. The piezoelectric ones are not appropriate for generating seismic waves in soil, and they require an elaborate electric device and electric power. Thus, 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.

Prototype In-hole Sources

The depictive description of the first prototype source is shown in Figure 5. 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. The manual pulling-wire triggering was replaced with a gear-servomotor device in the 2nd version shown in Figure 6. The recent version of the source consists of a spring-loaded impact pestle, a gear-servomotor triggering device, and a mechanical packer which is powered by two servomotors.

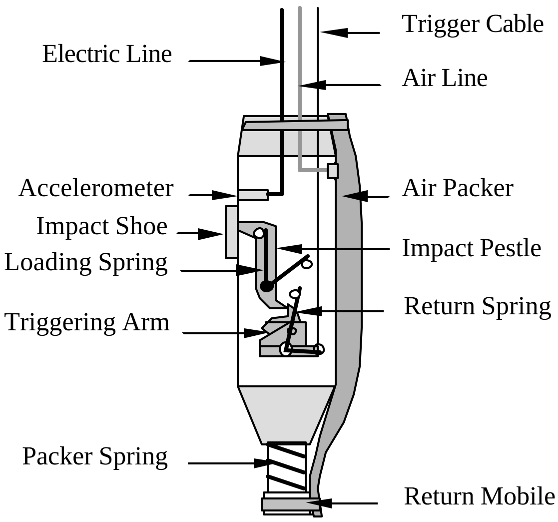


Figure 5. Schematic Diagram of Spring-loaded Source

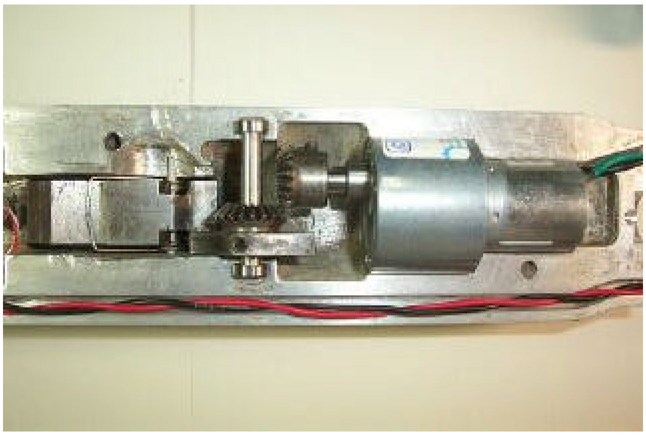


Figure 6. Second-version Source Showing a Gear-servomotor Triggering Device

PERFORMANCE OF IN-HOLE SOURCE

To evaluate the performance of the source, extensive crosshole tests were performed at various sites including Juk-jeon apartment site, and several benchmark sites for earthquake research at HaeMi-, SaCheon- and TongYoung-city in Korea (Kang, 2003; Kim, 2002; Mok et al., 2003). Typical compression and shear wave signals are shown in Figure 7. For P-wave measurements, source and receiver are oriented to face each other. The on-set of the first big trough of the signal is the first arrival of P-wave (designated with "P" in the upper figure of Figure 7). In shear measurements, source and receiver are placed perpendicular to the ray path. The on-set of 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 such identifiable P- and S-wave patterns respectively that the first arrival times can be easily picked. The source has been proven to generate excellent P- and S-wave energy.

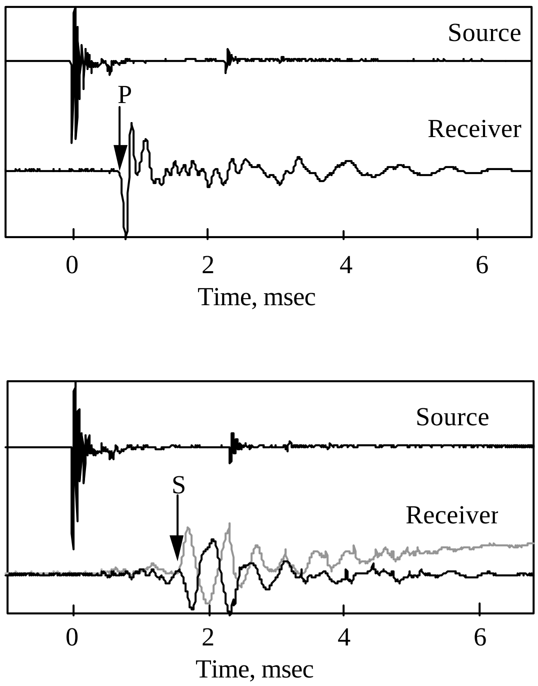


Figure 7. Typical P-wave and S-wave Crosshole Signals Generated with the Manual Version of the Prototype Source

IN-HOLE TESTING

Soil Site

An in-hole probe was assembled with the in-hole source, one receiver (Mark Products, 4.5Hz geophone), and a connecting rod (isolator) as shown in Figure 8. The recording system is HP35670A dynamic signal analyzer. The distance between impacting and monitoring points was 1 meter. Uncased boreholes were drilled to the depth of about 7 meters for in-hole and crosshole testing at a five compaction fill site for railroad load-bed construction. In the crosshole testing, the same source and receiver used in in-hole testing were used. The shear wave signals, measured by in-hole and crosshole testing at every 0.5 meters at site 2, are shown in Figure 9 and Figure 10, respectively. The first arrival times of the shear waves are indicated with a black dot in the figures. The shear wave signals are distinctive enough to pick up the first arrival of shear energy. Two measurements agree well in the range of shear wave velocity of 230 m/sec to 300 m/sec as shown Figure in 11. 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.

Figure 8. Recent Version of In-hole Probe

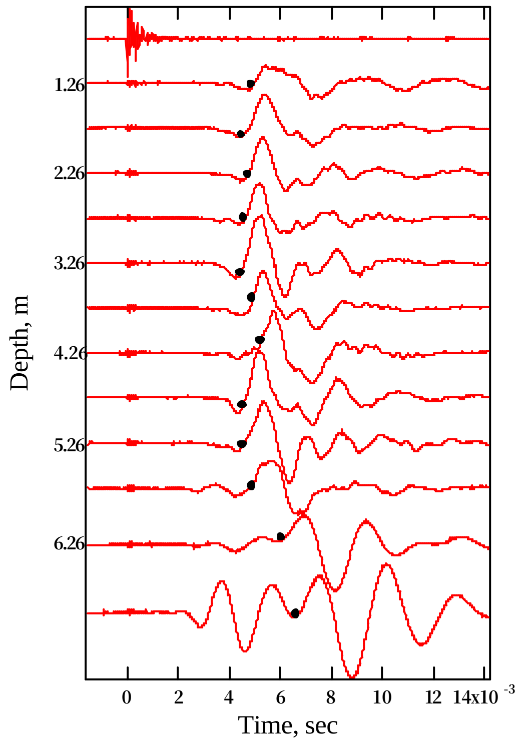


Figure 9. Shear Waves Signals Measured From In-hole Testing at Site-2

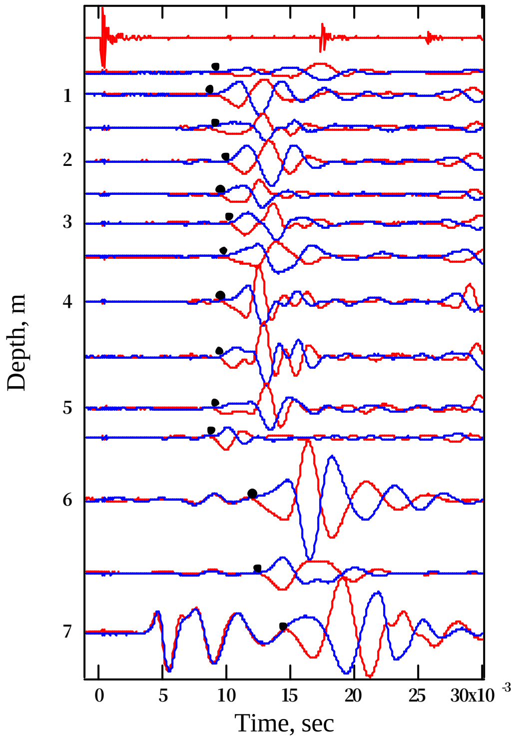


Figure 10. Shear Wave Signals Measured From Crosshole Testing at Site-2

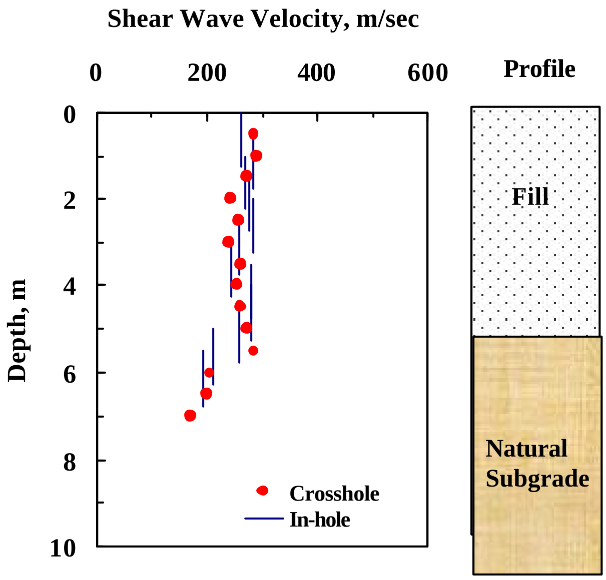


Figure 11. Comparison of Shear Wave Velocity Profiles Determined Form In-hole and Crosshole Tests

Rock Site

The probe was lowered 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 at Sumjin-Dam site in Korea (Kang, 2003; Kim, 2002). In the rock layer, distinct shear waves were measured as shown in Figure 12 and 13. The typical shear wave signal shown in Figure 12 is distinctive enough to pick up the first arrival of shear energy (denoted by "S"). The predominant frequency and wave length of shear waves are of 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 2.1 meter apart from the original borehole to conduct crosshole testing, in which the same in-hole source and receiver as used in the in-hole measurement. And the measured S-waves are shown in Figure 14. Comparison of the average shear wave velocity profiles from companion tests are presented in Figure 15 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. In 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.

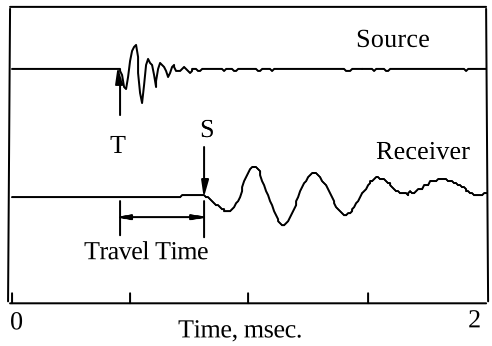


Figure 12. A Typical Shear Wave Signal From In-hole Test

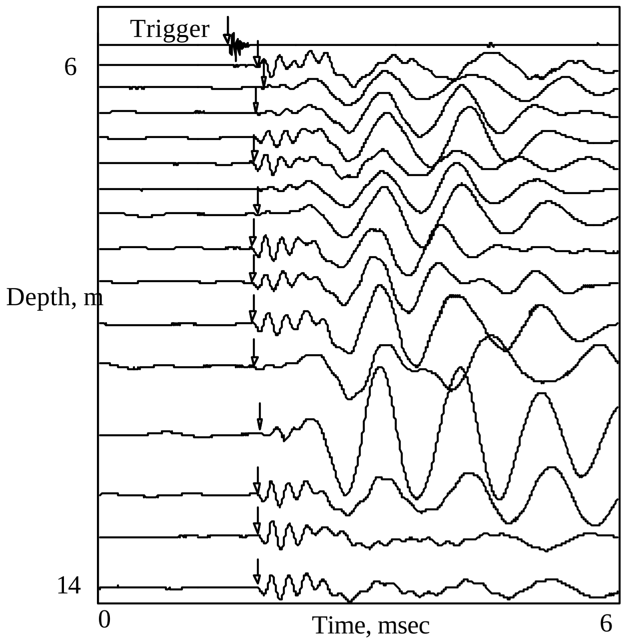


Figure 13. Shear Wave Signals from In-hole Tests

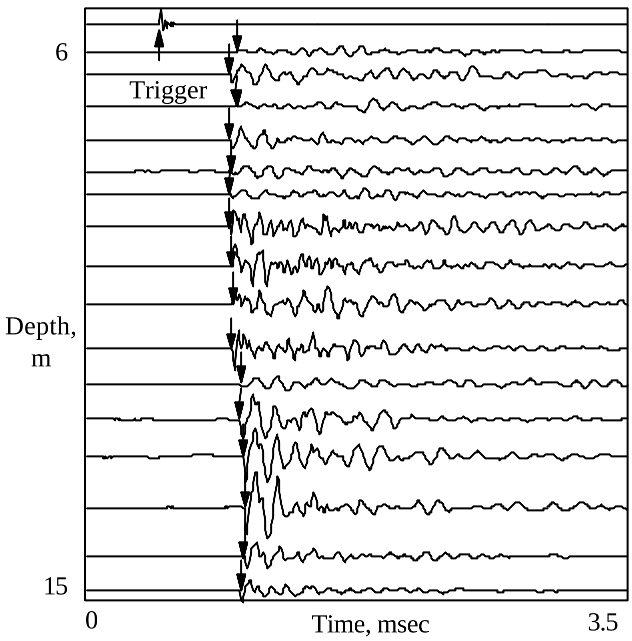


Figure 14. Shear Wave Signals from Crosshole Tests

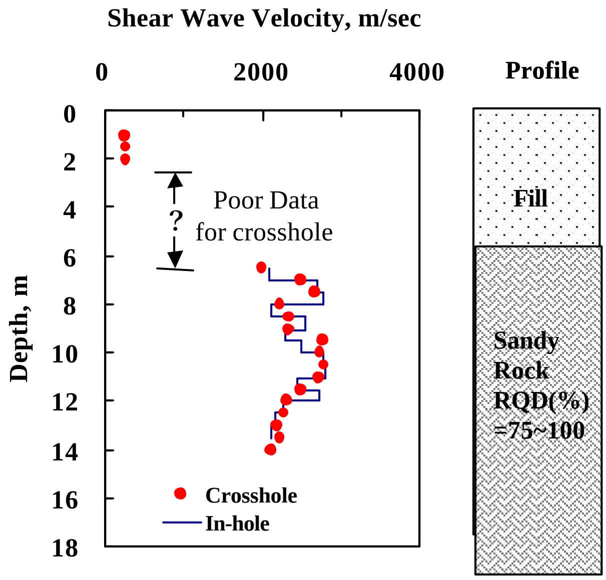


Figure 15. Comparison of Shear Wave Velocity Profiles Determined From In-hole and Crosshole Tests

CONCLUSION

In-hole seismic method has been developed to be used practically by geotechnical earthquake engineers in the areas of measuring dynamic subsurface material properties for earthquake-resistant designs. The in-hole probe and testing technique has been adopted various sites and proven to perform reasonably well by comparison with crosshole test results. Presently, the method is very cost effective and easy to use in residual soils, compaction fills and rock where uncased boreholes can stay open. The technique is being implemented with SPT rods for deeper exploration in collapsing soils.

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