RECENT DEVELOPMENT OF BOREHOLE SEISMIC TESTS

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ABSTRACT :

In an extended effort to improve the borehole seismic methods, an in-hole seismic source has been developed and utilized in cross-hole and in-hole seismic measurements. The source has been developed to be fit in three-inch (76 cm) boreholes with key functions including a spring-loaded impact pestle, a servomotor triggering device and a mechanical coupler driven with two servomotors. The spring-servomotor mechanism of the source makes it possible to be used in uncased boreholes as well as cased ones. The source enables to reduce testing cost and to improve the accessibility of borehole seismic methods to practice engineers. Also the source can be incorporated to an in-hole probe for in-hole seismic method, which is performed in a single borehole so that the testing cost could be cut down further. The performance of the source has been evaluated with cross-hole and in-hole measurements at various sites.

KEYWORDS : In-hole Source, Borehole Seismic Methods, Shear Wave Velocity

1. INTRODUCTION

The shear wave velocity is one of key parameters in the characterization of local grounds for geotechnical earthquake engineering problems. Incessant efforts, to measure the parameter accurately, have been made involving borehole seismic and nondestructive surface wave techniques over several decades. In an extended effort to improve the borehole seismic methods, an in-hole seismic source has been developed and utilized in cross-hole and in-hole seismic measurements. The source has been developed to be fit in three-inch (76 cm) boreholes with key functions including a spring-loaded impact pestle, a servomotor triggering device and a mechanical coupler driven with two servomotors. The spring-servomotor mechanism of the source makes it possible to be used in uncased boreholes as well as cased ones. The source enables to reduce testing cost and to improve the accessibility of borehole seismic methods to practice engineers. Also the source can be incorporated to an in-hole probe for in-hole seismic method, which is performed in a single borehole so that the testing cost could be cut down further (Park et al., 2008). The performance of the source has been evaluated with cross-hole and in-hole measurements at various sites.

2. SEISMIC SOURCES

The primary function of a source is to generate identifiable P- and S-waves. The key requirement of the source is directional, repeatable and high signal-to-noise ratio wave energy. Because of S-waves being masked by the P-wave train and by the other waves following after the initial P-wave arrival, identification of the initial S-wave arrival can be difficult. Therefore, major endeavor has been focused on the development of S-wave sources over the several decades. Three types of borehole seismic sources, such as mechanical wedge, solenoid, and piezoelectric types, have been developed and successfully used in crosshole testing in geotechnical engineering applications. These sources offer insight into the design of the new in-hole source developed herein.

2.1. Mechanical Wedge-Type Source

Among various mechanical sources, the most updated one is a wedge, composed of four jaws and two cones activated by a double-acting air cylinder, upon which a pair of rams is banged, in both downward and upward directions (Mok et al., 1999). The reversed impacts generate vertically polarized S-waves of reversible initial polarity, which show “butterfly pattern” and enable, in turn, to pick the first arrival of the wave. This source has been used at numerous sites and has proven to be an excellent seismic source in the crosshole test. This source is usable in cased boreholes only, because of necessity of firm grip against borehole wall.

2.2. Piezoelectric Source

The piezoelectric source, such as “BeBop (Roblee et al., 1994)” and “GeoPing (Paik et al., 1997),” utilizes the behavior of piezoelectric materials, which change physical dimensions when subjected to an electric field. 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 signals. Moreover, through reversing the radial orientation of source impact, S-wave arrival time can be clearly seen using the reversal in the horizontally polarized S-wave motion. However, the primary drawbacks of the source are the complexity and cost. In addition, deformational amplitude generated from the piezoelectric source is very small so that the source is not optimized for less stiff materials such as soils.

2.3. Solenoid-Coil Type Source

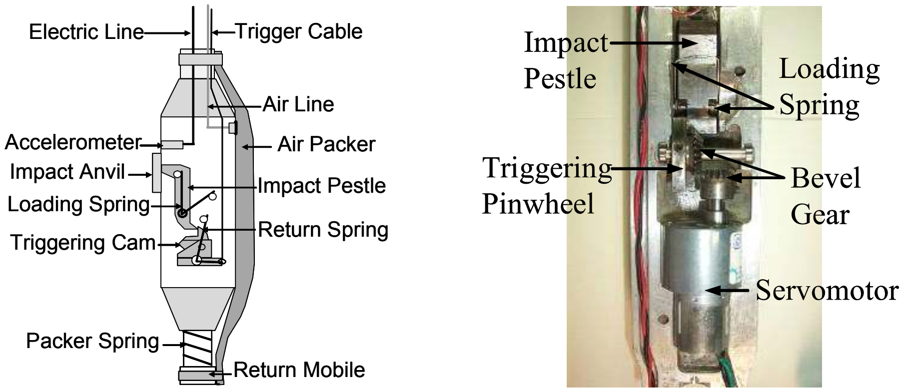
A moving coil type electromagnetic exciter consists of a bobbin assembly functioning as the exciter and a hollow cylindrical coil. The coil is set in the gaps where the magnetic field is produced by a permanent magnet. A driving current is applied to the coil so that a bobbin assembly strikes the plate, which is in the inside of the source. If the current is switched in the opposite direction, the excitation direction is reversed. Solenoid-coil system is generally used as indirect-excitation type source in the suspension P-S logging (Kitsunezaki, 1980). Fuhriman (1993) and Roblee et al. (1994) developed the solenoid source, called “Dizzy,” for soil application. The source is designed to fit within 4 inch (13 cm) diameter or larger cased boreholes. This source generates a radially oriented stress pulse on the limited region of the borehole wall. The active element for this source is a high-force electromagnetic solenoid, the plunger of which directly impacts a hardened steel pin mounted on the inner surface of the impact foot. This source mechanism creates a signal rich in energy between approximately 50 and 1000 Hz. Since soil is a highly attenuating media, use of this lower frequency band is desirable as a means to achieve requisite signal-transmission distances.

3. ELECTRO-MECHANICAL SOURCE

The mechanical wedge-type source is very rugged, but the operation is somewhat labor-intensive. The source cannot be used in uncased boreholes and physically is too large to be integrated into the in-hole probe for in-hole seismic method. The piezoelectric ones are not appropriate for generating seismic waves in soil, and require so elaborate an electric device that maintenance and repair are not easy. Commercial off-the-shelf solenoids, which are small enough to be fit in 3 inch boreholes and powerful enough to generate proper energy in soil, are not available. The one integrated with the best effort made by Roblee et al. (1994) can be fit in 4 inch borehole at most. The target features of the source, set in the study, include simplicity and ruggedness of the device, sufficient energy for use in soil, easy field operation, and being small and light enough to be fit in 3 inch cased or uncased boreholes. Thus, a spring-loaded mechanism controlled by servomotor, was adopted and the prototype has been refined.

3.1. Prototype of Spring-Loaded Source

The depictive description of the first prototype source is shown in Figure 1(a). The basic operating principles of the first primitive source are such that the trigger-cam releases a spring-loaded impact-pestle by pulling the trigger-wire, thereby impacting the borehole wall and reloading the impact-pestle automatically by a return-spring (Mok et al., 2003). The inflated air bag ensures intimate contact between impact shoe and borehole wall and enhances impact energy delivered directly into geologic material. Its performance proved the soundness of the concept even though the manual operation was cumbersome. The manual trigger was replaced by a set of gear gadget driven by a servomotor for easier operation in the 2nd version of prototype as shown in Figure 1(b).



(a) Prototype (b) Revised

Figure 1 Schematic diagrams of prototype and revised version of spring-loaded source

3.2. Refined Version

The latest version of the source consists of a spring-loaded impact pestle, a gear-servomotor triggering gadget, and a mechanical coupler as shown in Figure 2. The source is triggered by the servomotor, which rotates as slow as 8 RPM (revolutions per minute) under 24 voltages. The motor rotates a pair of bevel gears, contacted at right angle, and spins in turn the pinwheel. The revolving action of the pinwheel strains the pestle spring and releases the impact pestle. The impact pestle strikes on the impact anvil, which is contacted against borehole wall intimately by the coupler. The coupler is operated by a pair of the rotating spur and translating push gears, driven by a pair of servomotors. The mechanism of impacting and coupling enables the source to be used even in uncased boreholes. The source is operated by control unit at the ground surface. The companion receiver houses a horizontal geophone with the same mechanical coupler.

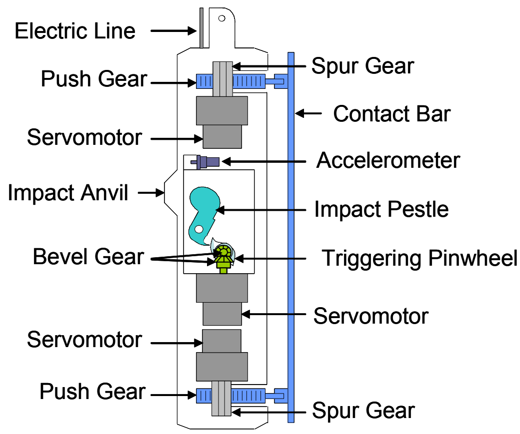
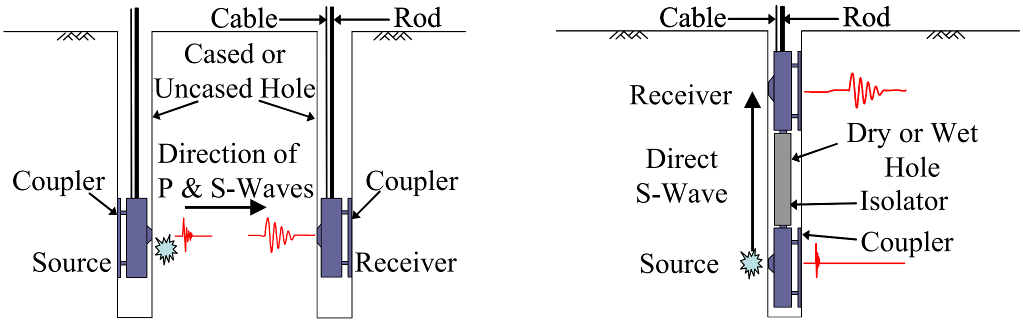


Figure 2 Schematic diagram of electro-mechanical source

4. PERFORMANCE

The source can be used in cross-hole and in-hole methods, the latter of which has been recently implemented thanks to the electro-mechanical source. The configuration of the tests is shown in Figure 3. The cross-hole needs at least two boreholes, one for source and the other for receiver. The in-hole method takes measurement by lowering in-hole probe, assembled with the source, connector, and receiver, down in the one borehole. The source generates the horizontal point impulse, so that P- or S- wave measurement can be achieved by orienting the source and receiver properly as shown in Figure 4. In cross-hole testing, P-wave can be monitored by facing the source and the receiver each other, aligned with the direction of wave propagation. For S-wave measurements in both tests, both the direction of the source impulse and of the receiver is oriented perpendicular to the ray path so that SH-waves are monitored. The performance of the source was evaluated through cross-hole and in-hole testing performed at various geologic materials including natural soil and rock sites, and embankment sites.



(a) Cross-hole method (b) In-hole method

Figure 3 Configuration of cross-hole and in-hole seismic methods

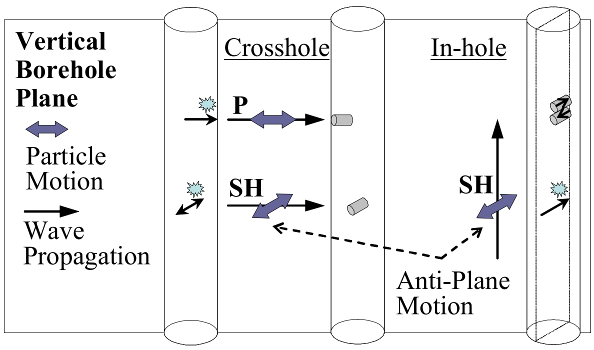


Figure 4 Orientations of source and receiver for borehole seismic measurements

4.1. Cross-Hole Method

The cross-hole test has been performed with uncased or cased boreholes. To asses the performance of the source, typical quality waveforms measured at various subsurface materials are presented herein. The quality cross-hole signals presented manifest the excellent performance of the electro-mechanical source.

4.1.1 Uncased boreholes

The typical P- and S-wave signals measured at a compaction fill (classified as SM) are shown in Figure 5. The on-set of the first big trough of the middle signal is the first arrival time of P-wave, as indicated with a dot. In shear measurements, a pair of shear wave signals was measured by reversing impact, as shown “butterfly” pattern in the lower signals. The on-set of the butterfly pattern, notated by a dot, is the first arrival time of the shear wave energy. The measured P- and S-wave velocities were 607 m/sec and 335 m/sec at the depths of 4 meters, respectively and resulted in Poisson's ratio of 0.28. The Center-to-center distance between the two boreholes was 2.14 meters.

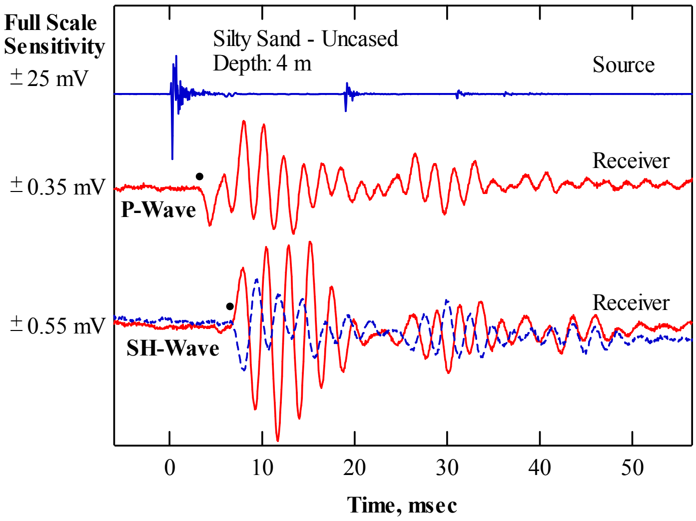


Figure 5 Typical cross-hole signals at a compaction soil site

Crushed-rock-soil fill was compacted for high speed railroad subgrade as high as 20 meters. The maximum size of the crushed rock was allowed less than 300mm. Two 76mm in diameter uncased boreholes were bored by a specialized percussion drill to the depth of 17 meters with the center-to-center distance of 2.6 meters. The typical P- and S-wave signals, measured at the depths of 6.5 meters, are shown and their first arrival times are indicated by a dot as shown in Figure 6. The measured P- and S-wave velocities, and Poisson's ratio of the compacted crushed-rock-soil were 708 m/sec, 420 m/sec, and 0.23, respectively.

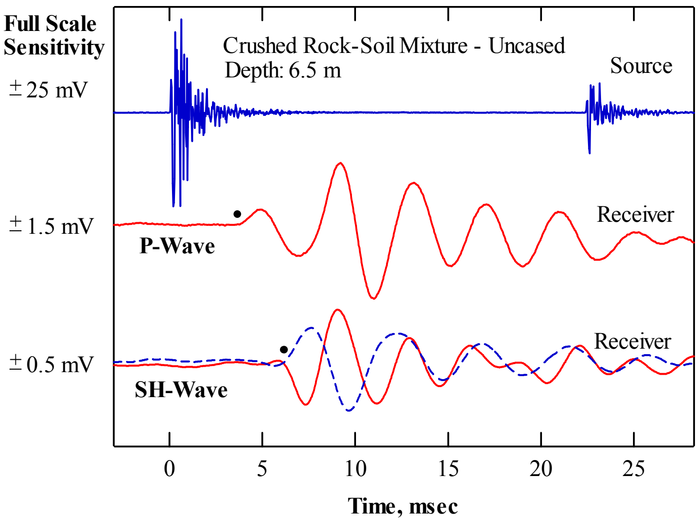


Figure 6 Typical cross-hole signals at crushed-rock-soil fill

Two boreholes 2.5m apart were drilled into the soft rock under a LNG(liquid natural gas) storage facility, near

Tongyeong-city, Korea. The rock was highly weathered as RQD (rock quality designation) and TCR (test core recovery) were reported as 0 % and 62 %, respectively. The typical signals of P- and S-wave signals, measured at the depth of 11 meters, are shown in Figure 7 and their first arrival times are indicated by a dot. The measured P- and S-wave velocities, and Poisson's ratio of the compacted crushed-rock-soil were 3,483 m/sec, 1,633 m/sec, and 0.36, respectively.

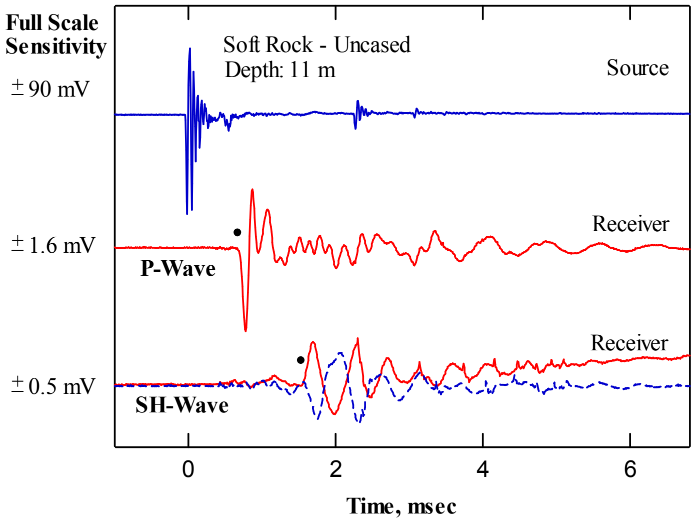


Figure 7 Typical cross-hole signals at soft rock

4.1.2 Cased boreholes

Among various geological materials, gravel or crushed stone is most picky material to handle, at which the cross-hole was performed with cased boreholes. Two cased boreholes, whose center-to-center spacing was 3.4 meters, were installed at a crushed rock sub-ballast site for an ordinary-speed railway, in Korea. The typical P- and S-wave signals, measured at the depth of 0.5 meters, are shown in Figure 8 and their first arrival times are indicated by a dot. The measured P- and S-wave velocities, and Poisson's ratio of the compacted crushed-rock-soil were 423 m/sec, 210 m/sec, and 0.34, respectively.

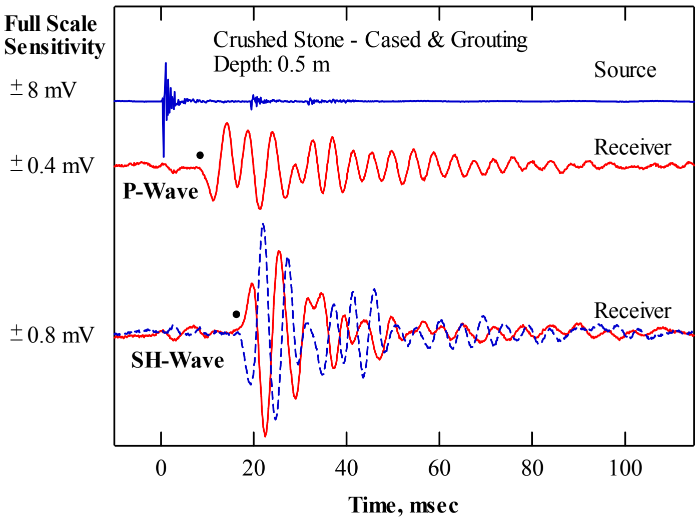


Figure 8 Typical cross-hole signals at a sub-ballast

4.2. In-Hole Meathod

The in-hole probe consists of three modules of the source, a receiver, and a connecting rod. The distance between source and receiver of the in-hole probe was 1 meter. The probe is operated by pushing the buttons of the control unit as shown in Figure 9. The probe was used at various sites for verification of in-hole seismic method (Park et al., 2008). The testing was carried out with uncased boreholes in non-collapsing geologic materials including compaction fills, weathered soil and bedrock. Only one case study is presented in the limited space of the paper. One uncased borehole was drilled on compaction fill site for railroad trackbed and in-hole testing was performed. Another uncased borehole was added to run cross-hole test to verify the in-hole test results. The in-hole data show the "signature wavelet" of the shear wave energy as shown in Figure 10(a). The dot symbols indicate the first arrival times of shear waves. The comparison of S-wave velocity profiles determined from in-hole and cross-hole results verifies the applicability of the source in in-hole seismic method as shown in Figure 10(b).

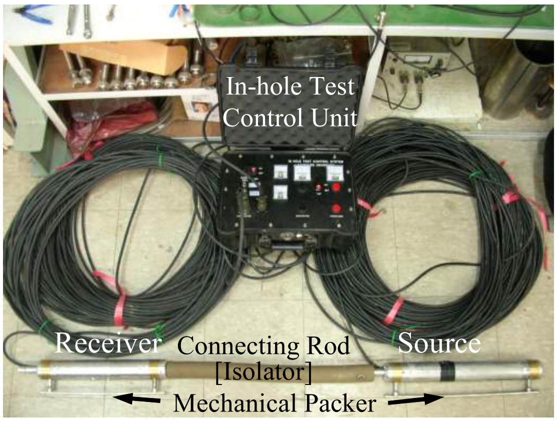
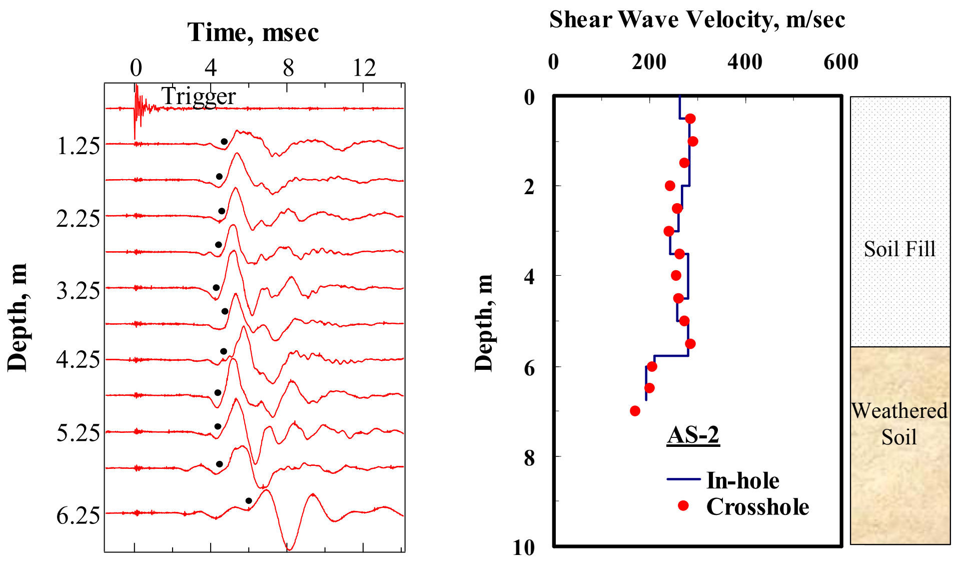


Figure 9 In-hole probe and control unit



(a) In-hole data (b) S-wave velocity profiles

Figure 10 In-hole test signals and S-wave velocity profiles

5. CONCLUSIONS

In an extended effort to improve the borehole seismic methods, an in-hole seismic source has been developed using spring-servomotor mechanism and utilized in cross-hole and in-hole seismic measurements. The source can be used even in three-inch (76 cm) uncased boreholes. The source enables to reduce testing cost and to improve the accessibility of borehole seismic methods to practice engineers. Also the source can be incorporated to an in-hole probe for in-hole seismic method, which is performed in a single uncased borehole so that the testing cost could be cut down further.

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