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A borehole seismic source and its application to measure in-situ seismic wave velocities of geo-materials

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ABSTRACT

A borehole seismic source was developed to measure horizontally-polarized shear (SH-) waves in the near surface and to improve drawbacks of conventional seismic sources. An electro-mechanical-type source, called "TahcBalm", has exceptional repeatability in generating signature SH-waves, while being sufficiently small and light to be fitted in 76 mm diameter cased or uncased boreholes. The source has been extensively used for borehole seismic testing at various locations with diverse soil and rock conditions. The cross-hole and in-hole testing signals are strong enough and allow the clear identification of the first arrival of SH-waves in all tested geologic environments. TahcBalm generates SH-waves with proper wavelength of about 1 m and 0.5 m for cross-hole and in-hole testing configurations respectively, at soil and rock sites. The source performs well in terms of data quality and ease of use.

1. Introduction

Civil engineering infrastructures that are designed to be resistant to earthquakes and man-made vibrations require accurate characterization of dynamic stiffness of local ground. S-wave velocity is an effective parameter representing the dynamic stiffness of ground in geotechnical engineering projects and is also extensively being used in static settlement and deformation estimations [4]. Borehole seismic testing is widely used to measure the S-wave velocities in the field. Several years ago, a new borehole seismic source was developed and presented its capability to measure signature P- and S-waves by the authors [20]. The source was developed by accounting for both advantages and drawbacks of conventional in-situ seismic techniques and seismic sources used in the field of geotechnical and earthquake engineering. In the study, the source, named "TahcBalm" (Korean phonetically-notated meaning finger flick), was adopted for cross-hole and in-hole methods at several locations including sites with natural and compacted soils, compacted crushed-rock–soil subgrade, crushed stone sub-ballast, and rock layers. The source can be used for materials with wide range of stiffness from as low as 100 m/s of S-wave velocity to thousands. The data for soft clay is not presented herein, for the reason of space, but referred [14]. The enhanced capabilities of the electro-mechanical source were evaluated through numerous field tests.

2. Borehole seismic tests and sources

2.1. Overview of borehole tests

In-situ seismic measurements have been used for several decades in the field of geotechnical engineering to evaluate P- and S-wave velocities for the dynamic stiffness at small strains. At small-strain levels, soil and rock may be considered to behave like linear-elastic materials [4,23]. For geotechnical and earthquake-related problems, the determination of in-situ S-wave velocity profiles of the ground is of most concern and various measurement techniques have been introduced. Of these measurement techniques, the in-situ seismic methods are divided into two groups: non-destructive surface method and borehole seismic method. The borehole seismic method includes cross-hole, in-hole, down-hole, and up-hole configurations as shown in Fig. 1. Additionally, suspension P–S logging has been used in seismic survey. These borehole techniques have been improved in terms of equipment

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and testing procedures, and have played an important role in site characterization [24,28].

The cross-hole seismic method generally results in more accurate and detailed profiles than other seismic methods [5,11,26,27]. However, this method often cannot detect thin slow strata sandwiched between two hard layers, and is expensive because two or more boreholes have to be drilled, cased and examined their verticality [1]. Additional efforts of grouting between casing and surrounding soil are required to ensure data quality. Decisively, the cross-hole method requires a sturdy and easily manipulable source that can withstand rough testing environments.

A version of in-hole seismic method [13,15,16] has been developed in past ten years to reduce testing costs and to promote the use, whereas the suspension P–S logging [7,10,17] has been used more than thirty years. The in-hole probe consists of three modules of a seismic source, one-dimensional horizontal receiver aligned with source impact direction, and a hard-rubber connecting rod which also can filter out the noise transmitted from the source. The source and receiver modules of the probe are pushed against borehole wall using a mechanical packing device. Polarized impacts can be directly delivered into the ground and the seismic signals rich in SH-wave are recorded with the receiver coupled intimately against the borehole wall. Therefore, the direct measurements of SH-waves can guarantee the consistency of signals and in turn accurate SH-wave time arrivals. On the other hand, suspension P–S logging uses water-coupling (the probe is suspended in the water filled the borehole) and pressure wave in the borehole fluid, and it measures converted and refracted waves; P-waves leave the source and arrive at the borehole wall, convert and refract to S-waves, travel up along borehole wall, convert and refract back to P-waves into the water, and finally arrive at the hydrophone [7,17]. Therefore interval measurements of travel time are necessary.

The down-hole seismic method is a representative technique, generally used in the seismic survey, to evaluate P- and S-wave velocity profiles [11]. Testing is conducted with a heavily-loaded

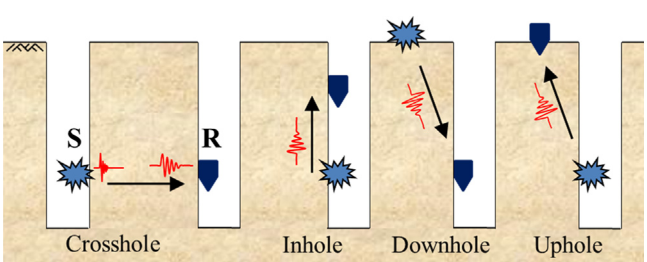

Fig. 1. Configuration of borehole seismic tests.

plank source on the ground surface and receivers placed at various depths in one borehole. Both sides of the plank source are transiently excited, and then a pair of horizontally polarized S-waves, in the opposite particle motions, can be observed. The down-hole method involves a test that is less expensive and simpler to perform in the field than the cross-hole test. The method results in rather smooth velocity profiles, especially when compared with the more detailed profiles determined by the cross-hole method [11]. In the case that a cavity is located along the ray path, or lower medium is much stiff than upper medium, the amplitudes of wave signals can be reduced. Also, as the measurement depth increases, the resolution and data quality decrease because ray paths and wavelengths become longer and longer.

The up-hole method is quite similar to the down-hole method [3,18]. The only difference is that the positions of the source and receivers are reversed. The source is placed in the borehole and the receivers are located on the surface. An explosive source is typically used which generates predominantly compression waves. As a result, the up-hole method is used very little in soil dynamics applications because of the need for S-waves in these applications.

2.2. *Previous seismic sources*

First, to generate identifiable P- and S-waves, the seismic source must be rich in generation of wave energy of concern so that a good signal-to-noise ratio is created. Second, the source should be directional so that the wave energy of concern is concentrated in one direction and thus receivers can be oriented to sense movement in the primary direction of wave particle motion. Finally, the source should be repeatable so that measurements made at one test location can be duplicated.

Because of direct S-waves being masked by the P-wave train and by reflected and/or refracted waves following direct P-wave arrivals, identification of the initial S-wave arrival can be difficult. Therefore, major efforts have been focused on the development of S-wave sources over the several decades. Three of the borehole seismic sources, such as mechanical wedge, solenoid, and piezoelectric types, have been developed and successfully used in cross-hole testing in geotechnical engineering applications. These sources offer insight into the design of the new borehole seismic source developed herein.

2.2.1. *Mechanical wedge-type source*

Mechanical sources are different, such as SPT hammering or vertical impulsive sources [3,18,24,28], torsional impulsive sources embedded below a borehole [9], and wedge-type source [2,11,12]. Among various mechanical sources, the most updated one is a wedge (Fig. 2(a)), composed of four jaws and two cones activated by a double-acting air cylinder, upon which a pair of rams is

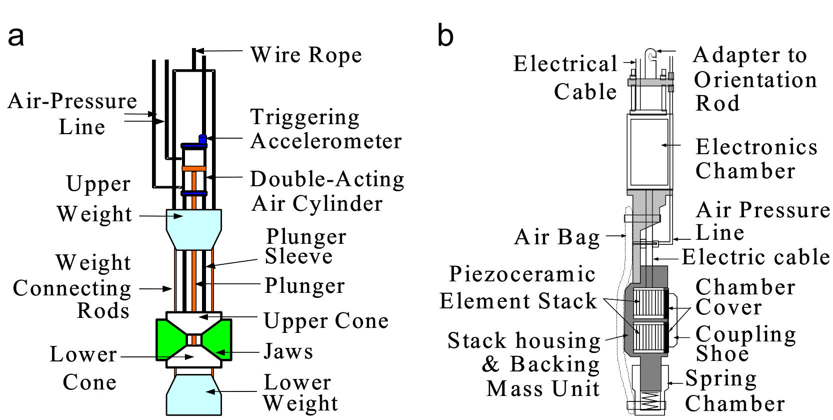

Fig. 2. Seismic sources: (a) mechanical wedge-type source and (b) piezoelectric source.

banged, in both downward and upward directions. The alternative impact directions generate vertically polarized S-waves with opposite polarities, 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 cross-hole tests. This source is usable in cased boreholes only, because of necessity of firm grip against borehole wall. Ballard borehole seismic source, being commercially available, is pushed against borehole wall by inflating a rubber air bag, and banged up and down to generate reversed signals abundant in vertically polarized S-waves [2].

2.2.2. Piezoelectric source

The piezoelectric sources, such as "BeBop [22]" and "GeoPing [19] (Fig. 2(b))", utilize the actuator capabilities of piezoelectric materials, which change physical dimensions when subjected to an electric field. Stacks of piezoelectric disks are charged with electric power, resulting in a stored distortion. Once fully charged, the electric field is quickly dissipated by shorting the circuit with a triggering signal, thereby rapidly releasing the stored strain energy in a transient seismic pulse. These sources provide excellent control and repeatability of the generated seismic signals [19,22]. Moreover, through reversing the radial orientation of source impact, S-wave arrival times 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 of the piezoelectric materials and maintenance. 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.

2.2.3. 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 strike direction is reversed. Solenoid-coil system is generally used as indirect-excitation type source in the suspension P–S logging [7,10,17]. The solenoid source of the suspension method produces energy between about 500 and 5000 Hz, and maximum spectral amplitudes of measured signals generally occur at about 1000 Hz for S-waves in stiff soils and soft rocks, corresponding to wavelengths of tens of centimeters [17]. Fuhriman [8] and Roblee et al. [22] developed the solenoid source for soil applications. The source is designed to fit within 100 mm (4-in.) 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 soils are highly attenuating media, use of this lower frequency band is desirable as a means to achieve requisite signal-transmission distances.

3. Development of an electro-mechanical source

3.1. Target features

The mechanical wedge-type source is rugged, but the operation is labor-intensive. The source cannot be used in uncased boreholes, and is physically too large to be integrated into the in-hole probe for the in-hole seismic method. The piezoelectric sources are not appropriate for generating seismic waves in soil, and require an elaborate electric device with which maintenance and repair are not easy. Commercial off-the-shelf sources using a solenoid is sufficiently small to be fitted into 76 mm boreholes and that generates proper energy in soils, however, it is not available because it cannot be performed in a dry or cased borehole (borehole fluid and fussy drilling process are always required), and it generally does not work well within 7 m of the ground surface due to the total length of the probe [7,25]. The one integrated source with the best effort made by Roblee et al. [22] can be fitted into a 100 mm borehole only. The target features of the source developed 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 fitted into 76 mm cased or uncased boreholes. Thus, a spring-loaded mechanism controlled by servomotor was implemented to the electro-mechanical borehole source.

3.2. Electro-mechanical source (TahcBalm)

The borehole source consists of a spring-loaded impact pestle, a gear-servomotor triggering gadget, and a mechanical coupler as shown in Fig. 3. The source is triggered by the servomotor, which rotates as slow as 8 RPM (revolutions per minute) under 24 V. 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 companion receiver houses a horizontal geophone with the same mechanical coupler. The source and receiver was designed to be used in cross-hole tests and in-hole tests as deep as 30 m. They are waterproofed and testing can be done in both dry and wet boreholes, and coupling and impacting operation of the probe are powered by 24 V battery set housed in control unit. The recording system is run by a portable 12 V battery. Both the source and receiver are manually oriented within the borehole with orientation rods which extend to the surface.

4. Borehole seismic testing

To evaluate the performance of the source, cross-hole tests and in-hole tests were performed at various geologic sites including natural soil and rock sites, and embankment sites. Generally, the measured signals vary in frequency, depending upon the soil and rock type. The wave field in this case can be treated approximately as that of a point single force in an infinite homogeneous medium, if the wavelength is sufficiently longer than the borehole diameter and if the distance between boreholes is much larger than the wavelength. Typical SH-wave signals measured at the sites (Asan-city for soil, and Seongnam-city and Tongyeong-city for rock, mentioned in Sections 4.3 and 4.4) were converted to amplitude spectra and in turn changed into wavelength for the horizontal coordinate as shown in Fig. 4. For soil, predominant frequencies cross-hole and in-hole test are in the vicinity of 220 Hz and 450 Hz respectively, which correspond to the wavelengths of 1.0 m for cross-hole and 0.5 m for in-hole test, from SH-wave velocity of 210 m/s. For rock, wavelengths of about 0.8 m and 0.4 m are obtained for cross-hole and in-hole tests respectively, from predominant frequency of 3.7 kHz and wave velocity of 3.1 km/s for cross-hole, and 5.3 kHz and 2.3 km/s for in-hole test. Typical source-to-receive distances used in cross-hole tests are in the

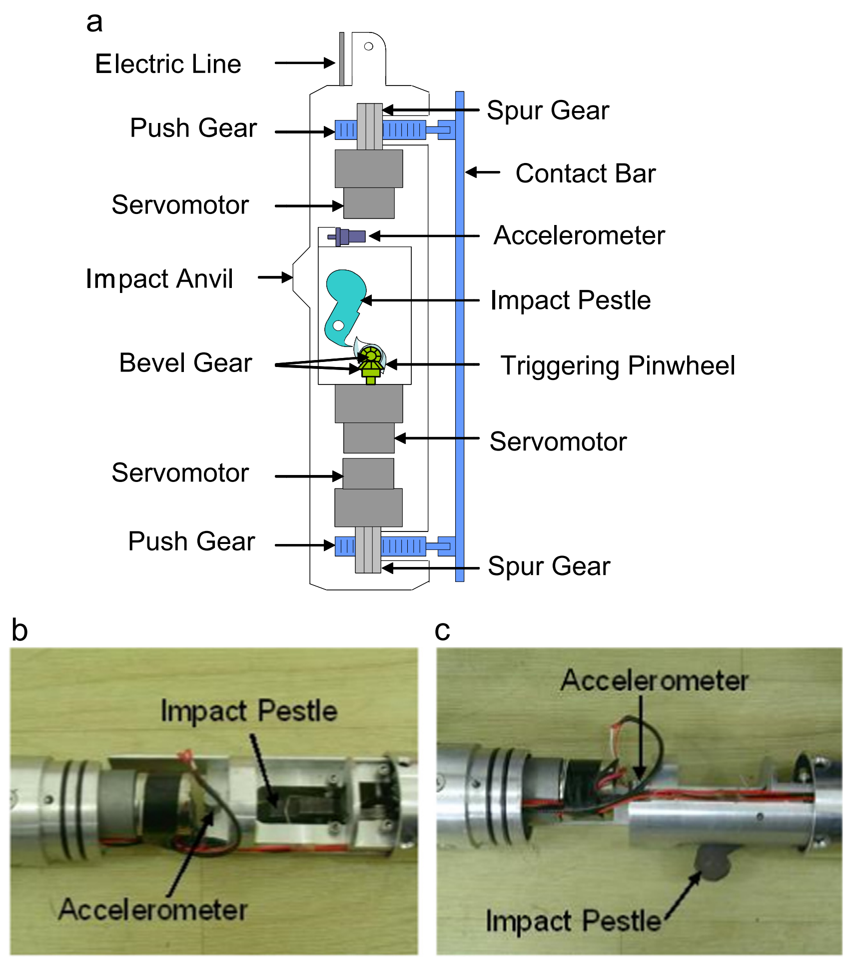

Fig. 3. Electro-mechanical source (TahcBalm): (a) schematic diagram; (b) inner front view; and (c) inner side view.

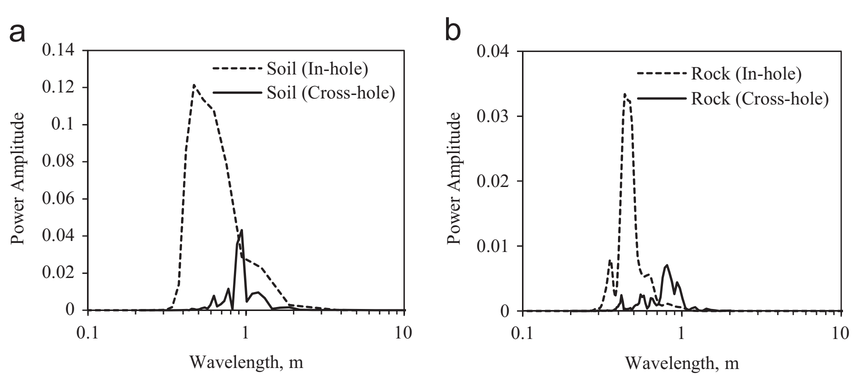

Fig. 4. Typical amplitude spectra of SH-wave signals: (a) soil and (b) rock.

order of 2–4 m and are in turn 2–4 times of the wavelength (about 1 m for soil and rock site). In the same way, the source-to-receiver spacing of the in-hole probe is fixed as 1 m and thus is a little more than twice of the wavelength. Therefore test set-ups of both cross-hole and in-hole tests are appropriate for the travel time measurements for SH-wave.

4.1. *Measurement configurations and wave types*

In cross-hole tests, P-waves are measured by having the direction of impact and the longitudinal axis of the receiver aligned (parallel) with the ray path as illustrated in Fig. 5. For S-wave measurements, both the impact direction and the receiver axis must be aligned perpendicular to the ray path. Reversed S-wave signals can be obtained by rotating the source 180° while holding the receiver in the fixed position. By overlapping a pair of reversed signals, a "butterfly pattern" of the opposed polarities of S-waves is presented for an accurate arrival time pick.

In in-hole tests, the same alignment as that used in cross-hole tests, is adopted for S-wave measurements except for the ray path; hereby vertical. The particle motion of the S-wave (in both cross-hole and in-hole tests) is out of the vertical borehole plane (anti-plane motion) and the wave is referred to horizontally-polarized shear wave (SH-wave) as illustrated in Fig. 5.

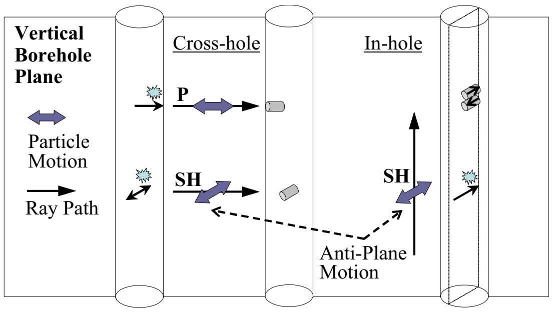

Fig. 5. Wave types for borehole configurations.

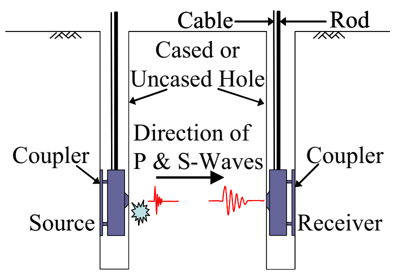

Fig. 6. Configuration of cross-hole seismic test.

4.2. Accuracy of velocity measurements

For measurement of travel time, "zero" reference point is taken at the sharp rising point of the electric trigger pulse as shown in Fig. 7(c). Although the trigger pulse is extremely repeatable, its timing does not coincide precisely with that of the actual initiation of the physical stress pulse of the source; there exists a trigger delay. Therefore, the zero reference point should be corrected with the delay. In the case of rock site (Fig. 7(c)), the trigger delay time of 22.8 μs was determined using the calibration procedure suggested by Roblee [21]. The value of the delay was subsequently used as a correction standard and was subtracted from all measured travel times. The zero reference correction is very important for the accuracy of direct travel time measurements between source and receiver [1].

The recording unit was an Agilent model 35670A dynamic signal analyzer. The sampling (digitizing) rates of 60 μs and 7.6 μs were set for soil and rock site, respectively. In subsequent S-wave signals, the errors associated with "first arrival time pick" were $\pm 2.5\%$ and $\pm 2.2\%$ for travel time of S-wave in soil and rock, respectively. With the S-wave velocity being in the range of 200–400 m/s for soil and 1.0–3.0 km/s for rock, the maximum errors of S-wave velocity of soil and rock correspond to ± 10 m/s and ± 100 m/s, respectively. Therefore the subsequent values of S-wave velocity were rounded down to tens for soil and hundreds for rock.

4.3. Cross-hole measurements

Cross-hole tests were performed using the developed source with uncased or cased boreholes (Fig. 6). To investigate the performance of the new source, typical quality waveforms measured at various subsurface materials are presented herein. The quality of cross-hole test signals manifests the enhanced performance of the electro-mechanical source.

4.3.1. Typical signals measured from cross-hole tests

The typical P- and SH-wave signals measured at a silty sand compaction fill are shown in Fig. 7(a). The onset of the first big trough of the middle signal is the first arrival time of P-wave, as indicated with a dot in the figure. In the shear measurements, a pair of shear wave signals was measured by reversing impact, as shown by the "butterfly" pattern in the lower signals. The onset of the butterfly pattern, notated by a dot, is the arrival time of the direct shear wave energy. The measured P- and SH-wave velocities were 610 m/s and 340 m/s at the depths of 4 m, respectively and resulted in Poisson's ratio of 0.28. The value may be bit high considering Santamarina's results [23]. The center-to-center distance between the two boreholes was 2.14 m.

Crushed-rock–soil fill was compacted for high speed railroad subgrade as high as 20 m. The maximum size of the crushed rock was less than 300 mm. Two 76 mm in diameter uncased boreholes were bored by a specialized percussion drill to the depth of 17 m with the center-to-center distance of 2.6 m. The typical P- and SH-wave signals measured at the depths of 6.5 m and the first arrival times indicated by a dot are shown in Fig. 7(b). P- and SH-wave velocity and Poisson's ratio of the compacted crushed-rock–soil were 710 m/s, 420 m/s, and 0.23, respectively.

Two boreholes 2.5 m apart were drilled into the soft rock under a liquid natural gas (LNG) storage facility, near Tongyeong-city, Korea. The rock was highly weathered as RQD (rock quality designation proposed by Deere [6]) and total core recovery (TCR) were reported as 0% and 62%, respectively. The typical signals of P- and SH-wave signals, measured at the depth of 11 m, are shown in Fig. 7(c) and their first arrival times are indicated by a dot. The measured P- and SH-wave velocities, and Poisson's ratio of the soft rock were 3500 m/s, 1600 m/s, and 0.36, respectively.

Among various geological materials, gravel or crushed stone is most easy to collapse, at which the cross-hole test was performed with cased and grouted boreholes. Two cased boreholes, whose center-to-center spacing was 3.4 m, were installed at a crushed rock sub-ballast site for an ordinary-speed railroad, in Korea. The typical P- and SH-wave signals measured at the depth of 0.5 m are shown in Fig. 7(d) and their first arrival times are indicated by a dot. The measured P- and SH-wave velocities, and Poisson's ratio of the compacted crushed-rock-soil were 420 m/s, 210 m/s, and 0.34, respectively.

4.3.2. Poisson's ratio determined from cross-hole test results

The records from the cross-hole tests (seen in Fig. 7) show such identifiable P- and SH-wave patterns; thus, the first arrival times can be easily identified, and all the opposing polarity SH-signals were clearly separated at any geologic medium. The P- and SH-wave velocities and Poisson's ratios calculated from the measured wave velocities are all reasonable values corresponding to typical geologic medium types. Poisson's ratios obtained from cross-hole tests using the electro-mechanical source are summarized in Table 1 along with soil and rock classifications.

4.4. In-hole measurements

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 is 1 m. The probe is operated by the control unit as shown in Fig. 8. The source and receiver are placed perpendicular to borehole axis and the direction of horizontally polarized S-wave propagation is parallel to the borehole axis as shown in Fig. 9. In-hole tests were conducted with uncased boreholes to avoid tube-wave interference, and the performance of the probe was verified through typical quality waveforms measured at soil and rock.

Fig. 10(a) and (b) shows the typical in-hole signals measured by the new source at weathered residual soils and two soil compaction fills (named fill-1 and fill-2), respectively. The onset of the first big surge is the first arrival of the shear wave energy. The dot

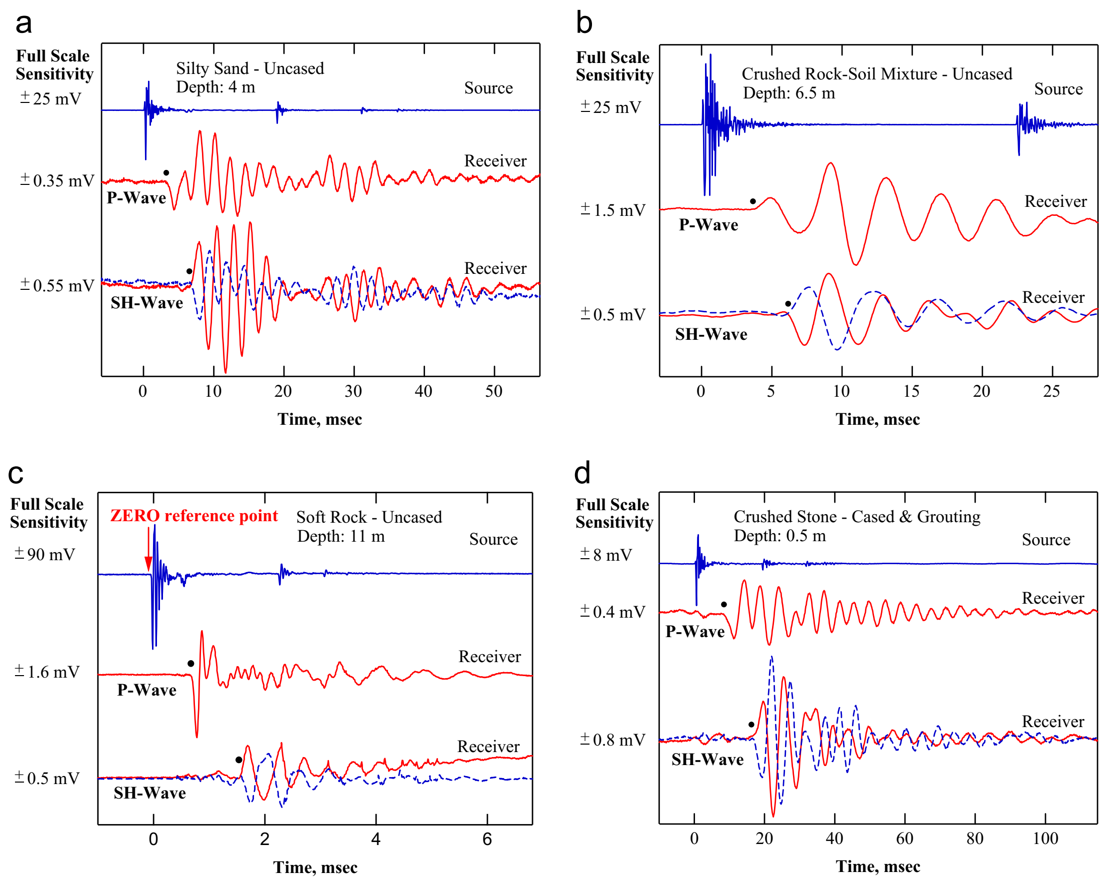

Fig. 7. Typical cross-hole signals: (a) compaction soil; (b) crushed-rock-soil fill; (c) soft rock; and (d) crushed stone sub-ballast.

Table 1
Poisson's ratio of soil and rock in Korea.

Classification	*Soil and Rock*	*Poisson's ratio, ν*	*Object (Location)*	*Note*
Natural soil	ML	0.48–0.5	Port quay (Incheon)	Marine, saturated
	SM	0.39–0.47	Railroad subgrade (Asan)	Saturated
	SM	0.27–0.35	LNG facility (Tongyeong)	Weathered soil
Fills	SM	0.28–0.32	Railroad subgrade (Asan)	Well-compacted
	SM	0.26–0.31	Bridge abutment (Hwaseong)	Well-compacted
	SM	0.30–0.36	Railroad subgrade (Pyeongtaek)	Well-compacted
	GP	0.28–0.37	LNG facility (Tongyeong)	Gravel sand
	GW	0.23–0.34	Railroad sub-ballast (Pyeongtaek)	Well-graded crushed stone
	Crushed-rock–soil	0.22–0.27	Railroad subgrade (Ulsan)	Max. particle size 300 mm
Rock	Weathered rock	0.26–0.36	LNG facility (Tongyeong)	Andesite
	Soft rock	0.22–0.36	LNG facility (Tongyeong)	Andesite
	Moderated rock	0.22–0.33	LNG facility (Tongyeong)	Andesite
	Hard rock	0.25–0.27	LNG facility (Tongyeong)	Andesite

symbols indicate the arrival times of horizontally polarized shear waves. The records from in-hole tests show such identifiable SH-wave patterns that the first arrival times can be easily picked as well as cross-hole records. The weathered residual soils had SH-wave velocity of 240 m/s at depth 0–1.0 m and that of 400 m/s at depth 3.5–4.5 m. SH-wave velocities are 290 m/s and 200 m/s at depth 3.0–4.0 m of fill-1 and 2.0–3.0 m of fill-2, respectively. The predominant wavelengths are about 0.5 m and SH-wave scans as deep as one wavelength (0.5 m) behind the borehole wall [7,25].

Shear wave measurements were carried out at hard rock and moderate layers at the depths of 6.0–7.0 m and 28.0–29.0 m, respectively, and the results are shown in Fig. 10(c). RQD and TCR of the rock core sampled from hard rock layer were 36% and 100%, respectively. In the case of the rock core sampled from moderate rock layer, RQD and TCR are 25% and 100%, respectively. The shear wave signals are sufficiently distinctive to pick up the first arrival of shear energy. The peak spectral amplitudes of SH-wave generated from the electro-mechanical source were at 5.5 kHz in hard rock layer and 6.7 kHz in moderate rock layer. Corresponding wavelengths behind the borehole wall of shear waves are 0.5 m and 0.45 m, respectively. SH-wave velocities of the hard rock and moderate rock layer of highway tunneling site were 2800 m/s and 3000 m/s respectively. Generally, shear wave velocities of rock mass are thousands of meters per second. Hence, the determination of precise travel time of shear wave is very significant under limited travel distance from source to receiver. The source developed in this study is suitable for identifying the shear wave arrival time at rock mass.

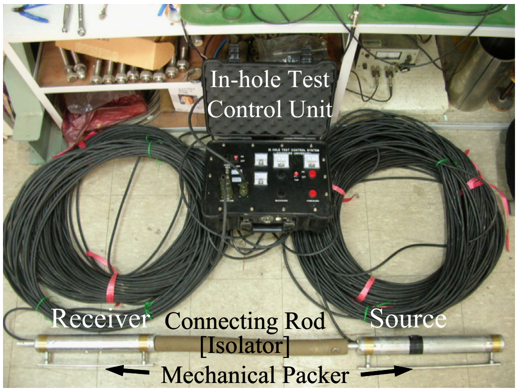

Fig. 8. In-hole probe and control unit.

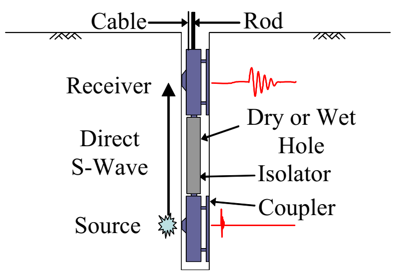

Fig. 9. Configuration of in-hole seismic test.

4.5. Verification of the performance of TahcBalm

4.5.1. Subgrade of railroad trackbed

Associated with the evaluation of resilient modulus for trackbed, in-situ seismic testing was performed at two sites near Asan-city, Korea. One uncased borehole was drilled on cutting site of weathered soil (called site AS-1) and two uncased boreholes were drilled on compaction fill site (called site AS-2). In order to verify the applicability of the in-hole source, in-hole and down-hole testing was performed at site AS-1 and in-hole and cross-hole tests were performed with the same source and receiver at site AS-2. Shear wave signals measured at each site are shown in Figs. 11 and 12. The in-hole data show the "signature wavelet" of the shear wave energy, and the dot symbols indicate the arrival times of shear waves. Stiffness profiles are shown in Fig. 13 with the result of cross-hole and down-hole tests. Shear wave velocities of the weathered soil increase from about 200 m/s to 400 m/s with depth, whereas those of fill are around 250 m/s. The comparison of S-wave velocity profiles determined from in-hole, cross-hole, and down-hole results verifies the applicability of the source in borehole seismic method.

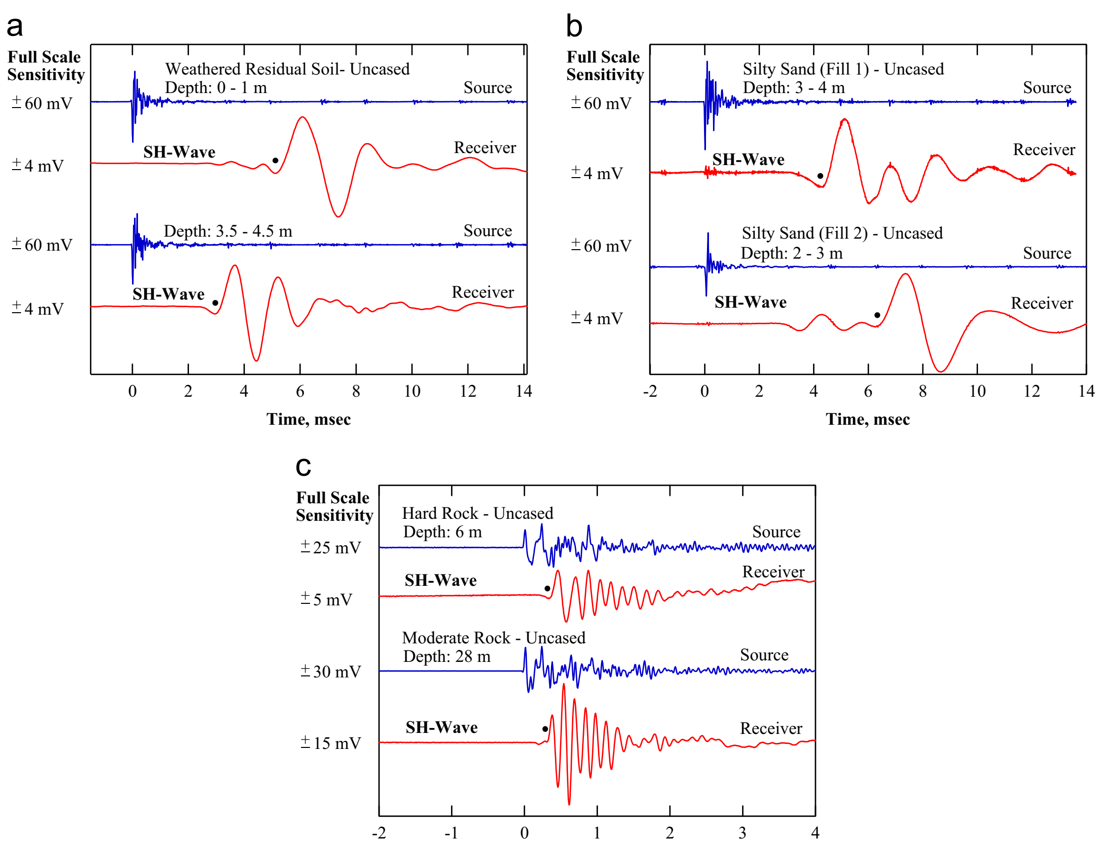

Fig. 10. Typical in-hole signals: (a) natural silty sand; (b) compaction soil; and (c) rock.

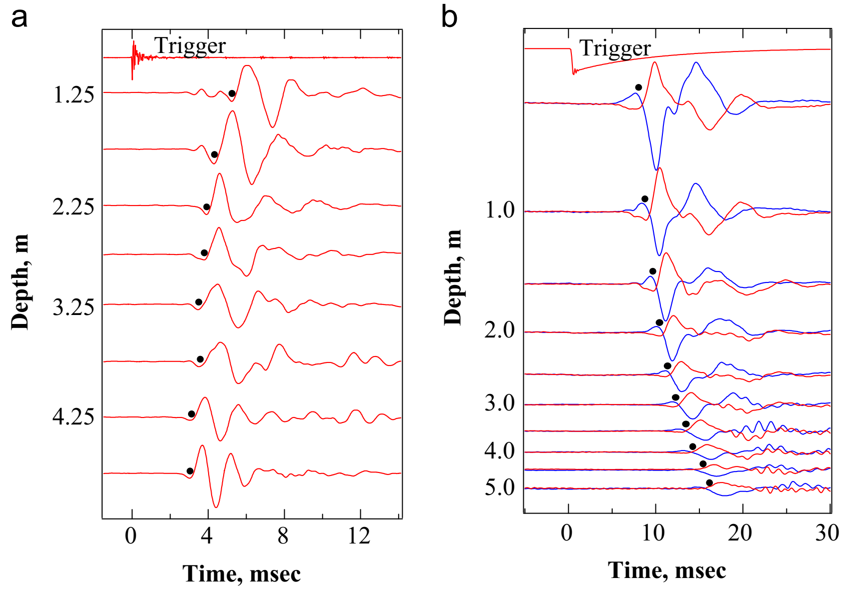

Fig. 11. S-wave signals at cutting site (AS-1): (a) in-hole seismic test and (b) down-hole seismic test.

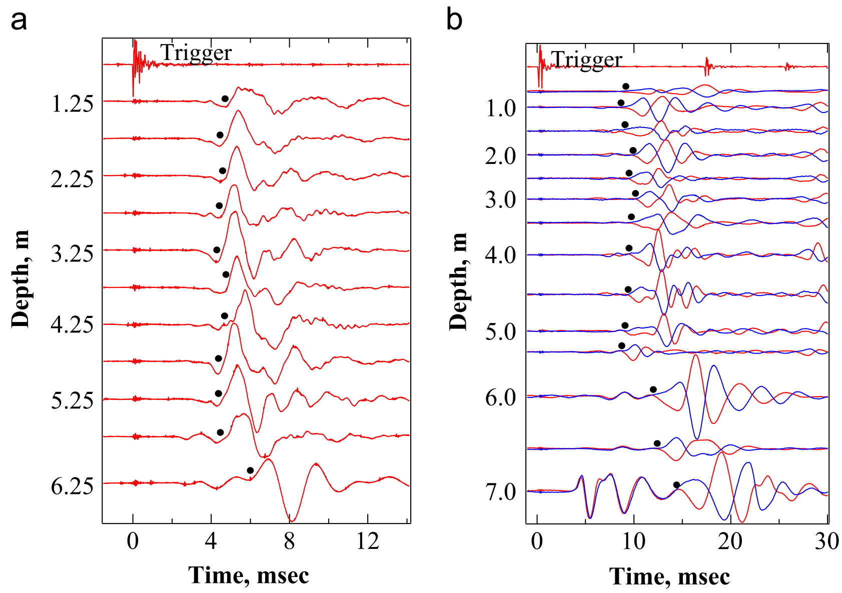

Fig. 12. S-wave signals at fill site (AS-2): (a) in-hole seismic test and (b) cross-hole seismic test.

4.5.2. Bedrock of tunnel and bridge

Shear wave velocities of bedrock were evaluated using in-hole seismic tests at highway tunneling (called SN-1) and bridge (called SN-2) sites, which were located at Seongnam-city, for earthquake-resistant designs. The geological formation of tunnel site consists of surface soil, weathered residual soil, weathered rock, soft (2.9–5.9 m) rock, hard (5.9–24 m), and moderate rock (24–32 m) of gneiss in sequence. The bedrock of bridge site was layered with surface soil and colluviums (3.4 m), soft rock (3.4–9.2 m), and hard rock (9.2–15 m). In the surface soil layers, in-hole test could not be performed because of the noise transmitted through the steel casing. The measured shear wave signals are shown in Fig. 14. The shear wave signals are distinctive enough to pick up the first arrival of shear energy (denoted by dot symbols). Shear wave velocity profiles and boring profiles including RQD are presented in Fig. 15. Shear wave velocities of the soft rock layer were 1200 m/s, those of the hard rock layer were 2000–3500 m/s with depth, and those of moderate rock layer were of the order of 3000 m/s at bedrock of tunnel site. Shear wave velocities of the soft rock layer were nearly 1500 m/s, and those of the hard rock layer about 2300 m/s at bedrock of bridge site.

4.5.3. Bedrock of rock fill dam

Shear wave velocities were measured to evaluate dynamic stiffness of bedrock at Doam rock fill dam in Korea, using in-hole and cross-hole seismic test. The testing locations were bedrock foundation (called site PC-1) and right side abutment (called site PC-2) of the rock fill dam. The geological profile of bedrock foundation consists of surface soil, sedimentary layer of sand and gravel, moderate and hard limestone with increasing depth as in Fig. 16. The geological formation of the abutment consists of surface soil and hard limestone. In the surface soil and sedimentary layers, shear wave measurements were not possible because of the noise transmitted through the PVC casing. Two more boreholes were drilled 2.5 m apart from the original boreholes (PC-1 and PC-2, respectively) to conduct cross-hole testing, in which the same

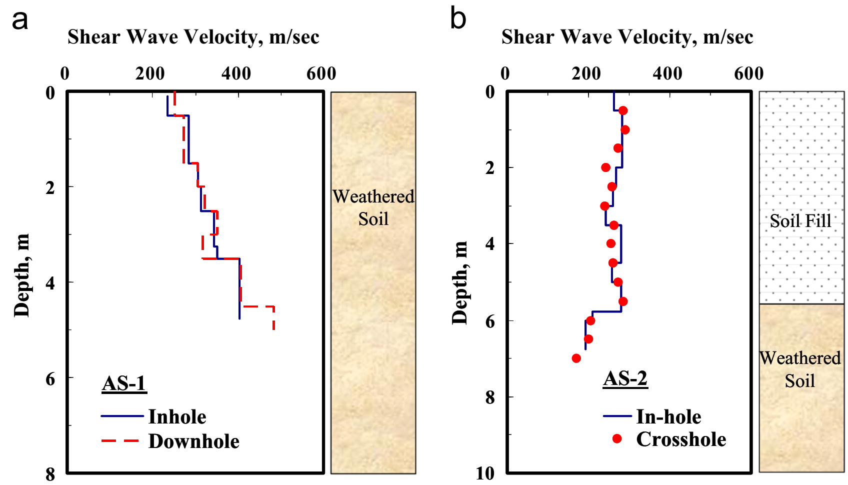

Fig. 13. S-wave velocity profiles of subgrade: (a) cutting site and (b) fill site.

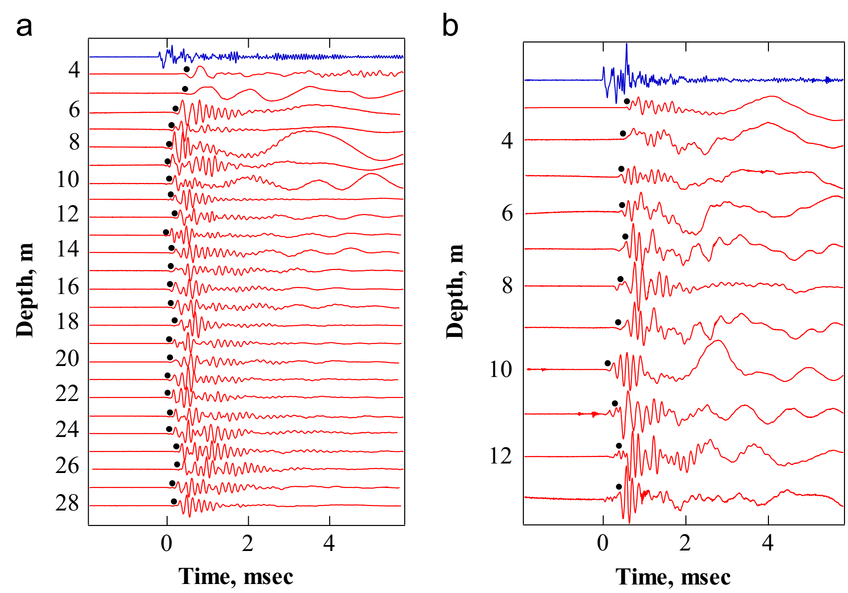

Fig. 14. S-wave signals measured from in-hole seismic test: (a) bedrock of tunnel and (b) bedrock of bridge.

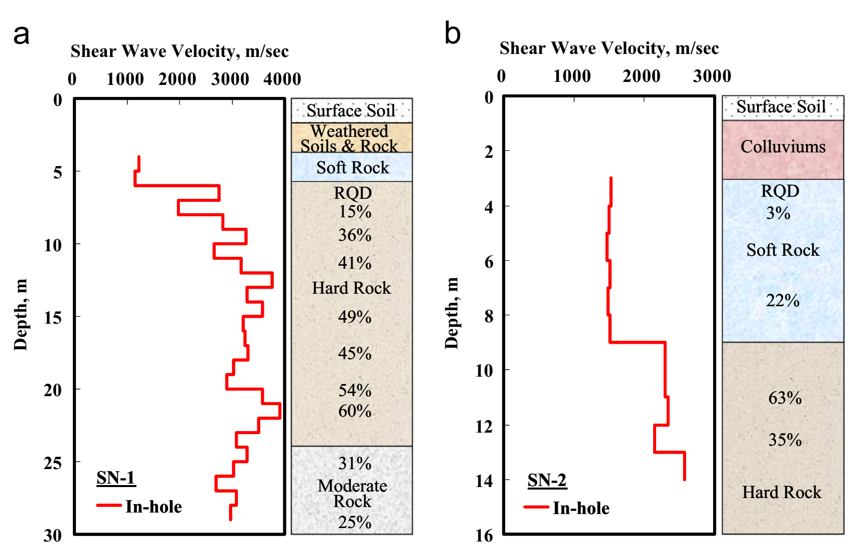

Fig. 15. S-wave velocity profiles: (a) bedrock of tunnel and (b) bedrock of bridge.

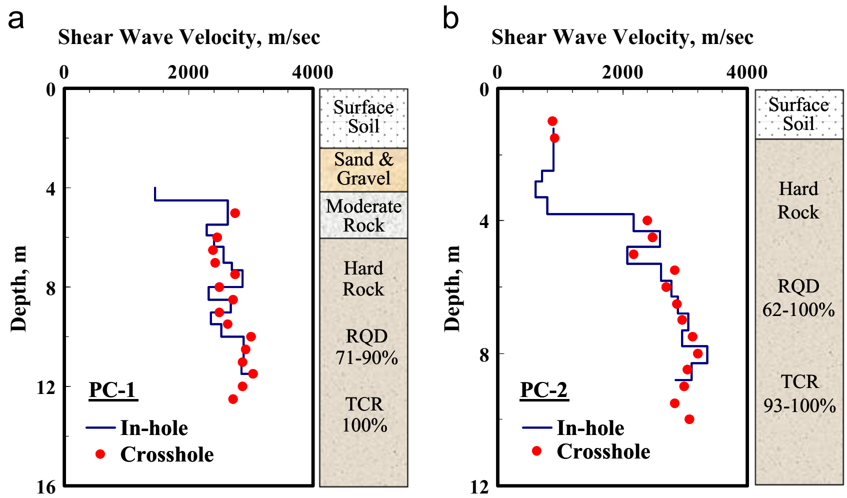

Fig. 16. S-wave velocity profiles: (a) foundation of rock fill dam and (b) right abutment of rock fill dam.

source and the receiver were used. The probe was lowered in a 76 mm diameter uncased borehole and shear waves were measured at every 0.5 m at the rock foundation and the right side abutment of dam, respectively. Shear wave velocities of the hard rock layer at foundation and right abutment were in the range of 2500–3000 m/s. Comparison of the shear wave velocity profiles with companion cross-hole tests is presented in Fig. 16 and shows good agreement.

5. Conclusions

In an extensive effort to improve the borehole seismic methods, a borehole seismic source (called TahcBalm) was developed using spring-servomotor mechanism and utilized in cross-hole measurements. The source can be fitted in 76 mm in diameter cased and uncased boreholes. In cross-hole tests, the source is now manually controlled with orientation rods for SH-wave measurements and the weight of rods in turn limits the measurement depth of around 30 m. In near future, TahcBalm will be further improved by implementing a self-orientation function into the probe and leaving out the manual control. The use of TahcBalm can be extended to be incorporated to an in-hole probe for in-hole testing. The in-hole probe can be coupled in borehole at two locations of source and receiver modules, bang impacts on borehole wall directly, and receive seismic signals rich in SH-wave. The probe can be used in uncased boreholes only because the tube-wave traveling along casing interferes in direct SH-wave and makes it impossible to identify the arrival time of SH-wave. The source generates SH-waves with proper predominant wavelength of about 1.0 m and 0.5 m for cross-hole and in-hole testing set-up respectively, at soil and rock sites. Therefore, TahcBalm was verified to generate excellent SH-wave at various geologic materials including weathered residual soils, soil fills, crushed-rock-soil subgrade, crushed stone sub-ballast, and rock layers. The source enables to reduce testing cost and to promote the use of borehole seismic methods.

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