

Two-dimensional imaging of soil–bedrock interface by short-array beamforming technique

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ABSTRACT

The depth to soil–bedrock interface, which is one of the major parameters in the site response analysis, has been often investigated by surface-wave tests. The round-robin tests for a surface-wave method in Korea revealed that a long measurement array in surface-wave tests is not appropriate in locating soil–bedrock interface. In this paper, for the improved profiling of depth to soil–bedrock interface in 2-D image, short measurement array was introduced for the beamforming technique, which is a robust array processing technique adopted in a long-array format for stiffness profiling. Numerical simulation and field applications of the short-array beamforming technique indicate that the method is valid even for surface wave propagation with mode-related complexity. Depth to soil–bedrock interface and shear-wave velocity profiles determined by the short-array beamforming technique were in good agreement with layer stratifications of boring logs, resistivity map, shear-wave velocity profiles of downhole tests and CAP-SASW tests.

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1. Introduction

For several decades in Korea, efforts have been made to investigate the depth to soil–bedrock interface for government projects, such as bridge piers, tunnels, large dams, and harbors. Seismic refraction survey used to be the only affordable geophysical approach for locating bedrock surface. In the late 1990 s, MASW [1] was introduced into the geophysical industry in Korea. Use of the MASW method was overwhelmed literally in all of the construction projects. With years, however, the MASW method was overtaken by borehole seismic tests, such as OYO's suspension logging, borehole tomography tests, and even downhole tests due to its lower accuracy than others. One reason for the lower accuracy of the MASW method in Korea is the complexity in geologic stratification and the shallow (mostly 3–30 m) depth of bedrock with localized undulation.

In this paper, elaborated research was performed to locate soil–bedrock interface of shallow undulating bedrock sites by surface-wave methods. The research was motivated by the round-robin tests performed in Korea to figure out the accuracy and reliability of various geophysical methods, including surface-wave methods and borehole seismic methods. One plausible cause of the lower accuracy found in the MASW method is that the MASW array is too long compared with the topological variation of the undulating

bedrock surface. Therefore, an alternative surface-wave method had to be sought, which utilizes a short measurement array. Finally, the beamforming technique [2,3] based on a short measurement array [4] was suggested. Herein, the word “short” in short measurement array is used twofold. First, it implies that the length of receiver array is relatively short, compared with the horizontal extent of investigation. Secondly, it indicates that the distance from the first receiver to the last receiver in measurement array is relatively short, compared with the distance from a source to the first receiver. Validity of the method was verified theoretically by analyzing synthetic seismograms for shallow bedrock, and experimentally by profiling 1-D and 2-D shear-wave velocity variations at two bedrock sites: crushed-rock fill over shallow bedrock and alluvial deposit at river side.

2. Difficulties in identifying undulating bedrock surface by surface-wave methods

2.1. Missing localized features in layer stratification

A geotechnical site with irregular undulation in its layers is a challenge to surface-wave methods. It is because the non-flat nature of soil or rock layers violates the assumption that the site should be laterally homogeneous. To investigate accuracy and reliability of surface-wave methods at shallow bedrock with a large dip angle, round-robin tests were organized at a natural geological site in Korea [5]. The round-robin tests were officially organized and supervised by Korean Geotechnical Society at an

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open geotechnical site in 2005, and all the geophysical specialists from universities as well as industries were invited. For the ground-truth profile, borehole seismic tests including downhole tests, inhole tests, and suspension logging were performed together. Borehole logs and SPT-N values for the test site in Fig. 1 (a) indicate that the bedrock surface of weathered rock plunges from a depth of 12–16.5 m in only 3-m distance. The rapid drop of the shallow bedrock is also observed by the resistivity map measured at the same site, as shown in Fig. 1(b).

Surface-wave methods, including MASW and CAP-SASW (Common-Array-Profiling Version of SASW) [6] and ReMi [7] methods that participated in the round-robin tests, produced 1-D and 2-D shear-wave velocity profiles. Resulting shear-wave velocity profiles are compared in Fig. 2 with the profiles by borehole seismic tests. Intuitively, it seems that surface-wave methods with a longer array produced a more smoothened version of shear-wave velocities. In this round-robin test, MASW tests used a 23-m measurement array, while CAP-SASW tests used a 3-m array. As expected, all the MASW tests conducted by three different specialists (denoted as MASW A, B, and C) reported lower velocities at a bedrock region than the velocities by seismic borehole tests. The existence of weathered rock could not be realized by any of the three MASW tests. Strong stiffness contrast between soil and underlying bedrock was diminished by the use of a long measurement array. Comparison of 2-D shear-wave velocity profiles by MASW and CAP-SASW tests brings the mitigation effect of the long array into more relief. That is, MASW profiles appear to be a smoothened version of CAP-SASW profiles. Two-dimensional resistivity plot in Fig. 1(b), measured at the same array as the one used for Fig. 2(b) and (c), supports the smoothening feature of the long array used by MASW tests. In Fig. 3, another comparison of 2-D profiles from both surface-wave methods was presented for a natural gravelly site at the riverside of GonjiAm, Korea.

The smoothening effect of the long array in the MASW method is also pronounced.

For the identification of undulation in a layered system, such as a drastic change in the elevation of soil–bedrock interface, a short measurement array in surface-wave tests is more suitable than a long measurement array.

2.2. Complexities due to mode collision in surface-wave propagation

Another concern in using a long measurement array is mode collision in surface-wave propagation. Mode collision indicates the phenomenon in which surface-wave data becomes complicated to analyze at the interface between two adjacent surface-wave modes. A typical example of mode collision can be found at the phase-difference spectrum determined by conventional SASW tests. In Fig. 4, conventional SASW tests were numerically simulated for the shallow bedrock model using the dynamic stiffness matrix method [8,9]. Dynamic stiffness matrix method has a capability to calculate apparent phase velocities for a given source and receiver locations. Synthetic seismograms in Fig. 4(a) were determined using a 45-m long measurement array with two receivers deployed at locations of 45 m and 90 m from the source, and they were used to generate impulse response equivalent to the pair of these two seismograms. In Fig. 4(b), the Gabor spectrum [10] for the impulse response clearly shows two different major wave groups, which are mutually interfered at the interface frequency of 8–12 Hz. At frequencies below the interface frequency, the wave group propagated through bedrock layer is a dominating wave group, whereas at frequencies above the interface frequency, the wave group travelling through soil layer is a dominating one. Interference of the two different wave groups is also observed at the phase-difference spectrum. That is, the phase spectrum in Fig. 4(c) is mixed up with the phase-difference spectra

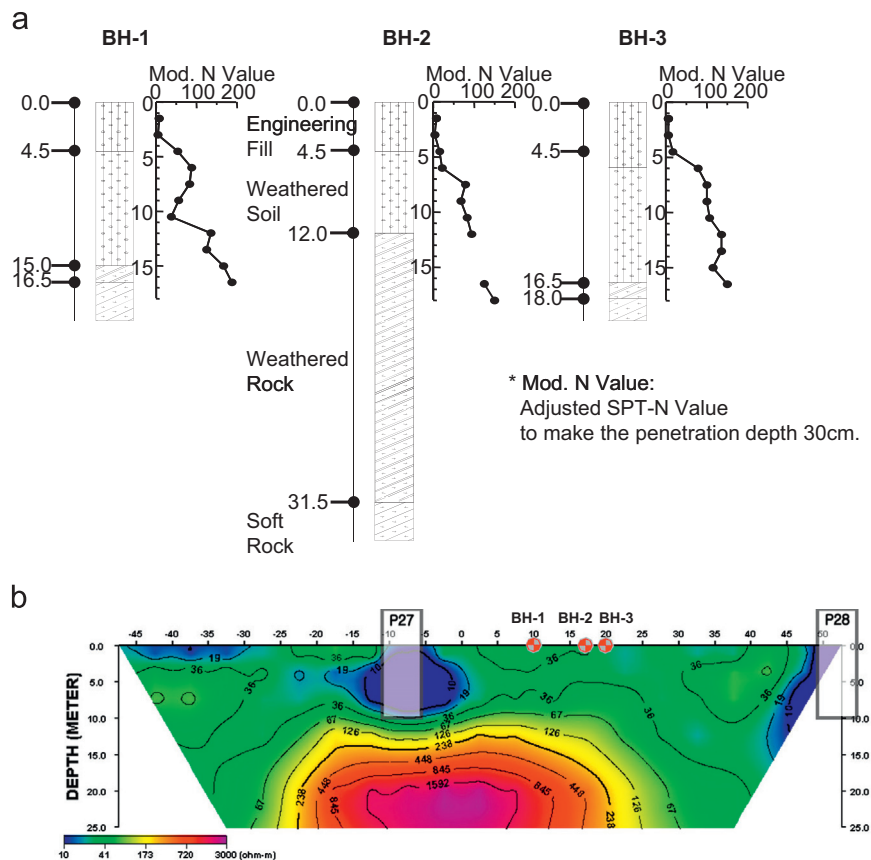


Fig. 1. Site description for round-robin tests: (a) borehole logs and SPT-N values and (b) 2-D variation in resistivity.

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