



Estimating the shear wave velocity structure above the fresh bedrock based on small scale microtremor observation array

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Received: 18 October 2018 / Accepted: 18 February 2020 / Published online: 5 March 2020
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Abstract

S-wave velocity and thickness of weathered strata are the important parameters to engineering construction. In this study, array measurements of microtremors were carried out at 50 sites in Jimo, China. It revised the observation array that a small scale array was placed in the center of traditional regular triangle observation array. The field data of Jimo verified that it is effective to identify the different degrees of weathered strata above fresh bedrock. Based on the spatial autocorrelation (SPAC) method, the dispersion curves were achieved. While the S-wave velocity structure was estimated using the fork genetic algorithm. By using small scale observation array, it identifies different strata including weathered layer in detail. In order to test the accuracy of inversion results, 5 sites were chosen to drill. Comparison between inversion results and boreholes, it shows agreement with logs data. At last, the S-wave velocity structures in different depths above the fresh bedrock were plotted. We delineated the S-wave velocity structure for the first time in this research region using revised measurement of microtremors signal. The depth of fresh bedrock fluctuates strongly which is affected by weathered. This method provides another means to distinguish the degree of weathered, depth of fresh bedrock, and S-wave velocity structure of shallow strata.

Keywords S-wave velocity structure · Sediments · Weathered strata · Fresh bedrock · Surface wave method based on passive source (microtremor)

Introduction

With the rapid development of urban areas, assessment of the depth of fresh bedrock/thickness of weathered strata is important for many applications (e.g., shallow foundations,

trenching). Geological information is critical to all the application. Among many geological parameters, S-wave velocity is a main ingredient in engineering geology. It can be used to calculate the physical and mechanics parameters such as shear modulus (G), Poisson ratio (μ), and elasticity modulus (E). At the same time, it has relation with standard penetration test (N), compressive strength, and yield strength of the rock foundation (Shen et al. 2015). Weathered bedrock and soil are part of the life sustaining layer (Clair et al. 2015). Estimating the S-wave velocity including weathered layer and sediments above the fresh bedrock is important to the construction and safety of urban area. For example, using the bedrock consolidation grouting, the parameters of weathered rock can be lifted to the level of fresh bedrock. Hence, it is a key task on how to estimate the S-wave velocity structure above the engineering bedrock especially the area where weathered strata are distributed.

Usually, S-wave velocity can be achieved using traditional seismic exploration methods or cross-hole tests. However, the borehole is costive. Traditional seismic exploration methods are effective but restricted by the civil conditions such that the signal resource is not friendly to environment. What's more, it loses function when there are weathered strata. In most area,

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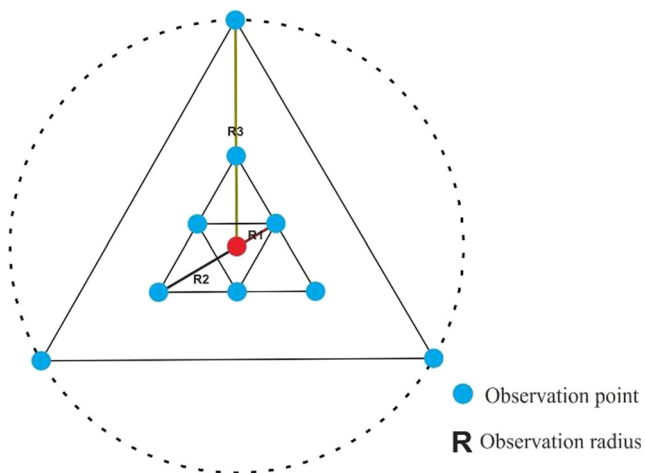


Fig. 1 Observation array of this study. The radius of small scale array is 1–2 m. The radius of traditional observation array is 5–10–20–40 m. In this figure, it shows the miniature array of 1–2 m and one traditional observation array of 5 m

weathered rock spreads widely. Surface wave method is used to achieve S-wave velocity now. Especially, the passive source surface method is widely adopted. Its signal resource is ambient noise that is not affected by observation environment. It has been applied to geothermal exploration (Tian et al. 2016, 2017), site-effect estimation (Chen et al. 2016; Ozlem et al. 2015), and mapping the depth of bedrock (Tun et al. 2016). Ambient noise usually is called microtremor or microseisms. Microtremor survey methods has become very popular because they are low cost, simple observation but effective. It originates from the research about ambient noise. The signal is recorded by a triangle observation array. The key step is the extraction of the field dispersion curve. Spatial autocorrelation

method (SPAC, Aki 1957) is the common technique to achieve dispersion curve from microtremor signal. It was applied to practical application after the revision of traditional SPAC method (Okada et al. 1990; Okada 2003, 2006). For example, it has excellent result to detect the S-wave velocity structure using the extended spatial autocorrelation method (Ohori et al. 2002; Rosa-Cintas et al. 2011). This method has reliable accuracy to obtain the S-wave velocity structure in deep crust (Matsuoka et al. 1996; Kudo et al. 2002; Estrella and González 2003; Tian et al. 2016).

In the shallow ground, microtremor survey method is a popular tool to investigate the sediment thickness or the depth of bedrock. Especially, it has high accuracy when the sediments overlay on hard bedrock such as to distinguish the interface between bedrock and overlain (newer) sediments or deposits. Ozlem et al. (2015) used it to explore the S-wave velocity structure of shallow soils. Most work are done in basin to estimate the shallow S-wave velocity structures, such as Taichung Basin of Taiwan (Satoh et al. 2001a, b), Sendai basin of Japan (Satoh et al. 2001a, b), Ljubljana Moor basin (Gosar and Lenart 2010), Puli basin of Taiwan (Wu and Huang 2012), Taipei Basin (Chen et al. 2016), Eskisehir basin of Turkey (Tun et al. 2016), and Bogota basin (Pulido et al. 2017). Similarly, microtremor array method was conducted in Kochi plain (Arai et al. 2012) and Banni plain (Sant et al. 2017) to identify the subsurface profiling, to improve the assessment accuracy of geothermal resources (Tian et al. 2020). Moreover, it is widely adopted in urban areas because of its versatility and minimal instrument requirements (Asten and Hayashi 2018). This method provides S-wave velocity structures of shallow soil formation and engineering bedrock for

Fig. 2 An example of SPAC coefficient of one observation array. s1 represents the survey site of observation array, R is the space distance, St represents the number of the station, Ndata represents the sampling points, Dt is the sampling interval, and Num is the episode number of the microtremor field data

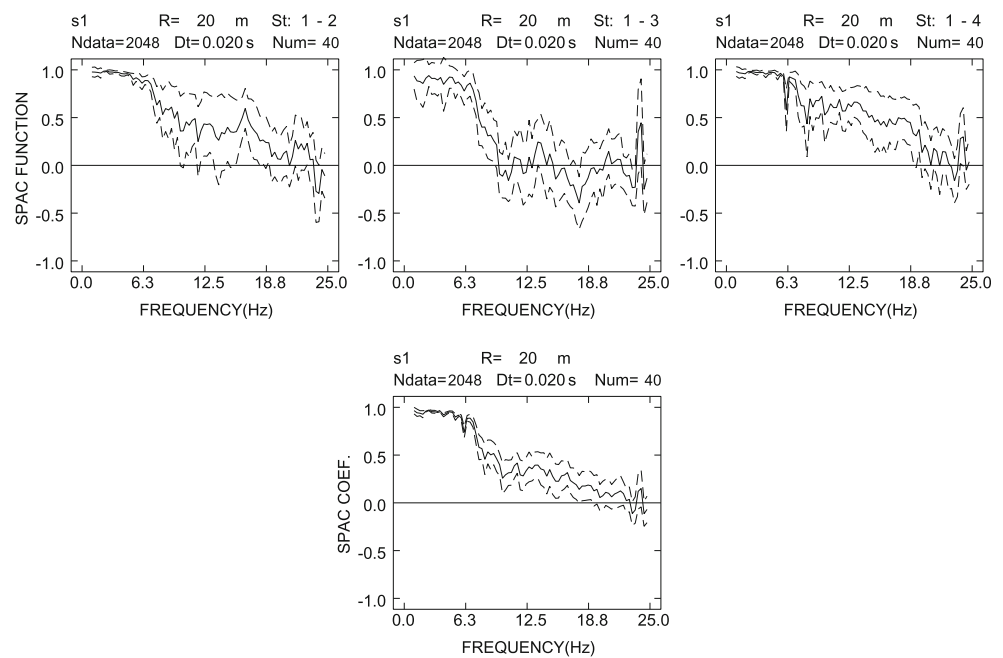
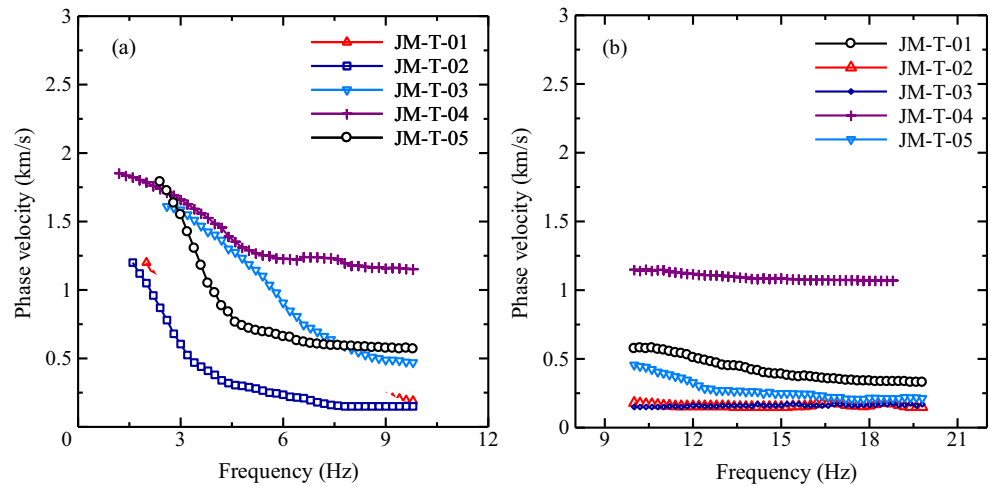


Fig. 3 Part dispersion curves of the observation sites. **a** The dispersion curves obtained from traditional observation array, the frequency of which ranges from 1 to 9.8 Hz. **b** The dispersion curve achieved from miniature array (1–2 m), the frequency ranges from 10 to 20 Hz



the development of infrastructure and high population density city (Zaineh et al. 2012; Ridwan et al. 2014, 2015; Mantovani et al. 2018). But the commonly used triangle configurations have relatively low resolution to the shallow ground especially where there are different degrees of weathered strata.

At the same time, microtremor array method combines with H/V spectral ratio method (single station technique) to identify the S-wave velocity of shallow ground. Using H/V spectral ratio method can determine the depth of bedrock and thickness of subsoil effectively (Bodin et al. 2001; Francesco et al. 2013; Guo et al. 2014; Rincon et al. 2016; Erkan et al. 2017; Tian et al. 2019). Joint inversion of dispersion curve and H/V spectral ratio curve provides more accurate results about the bedrock (Arai and Tokimatsu 2005). Picozzi et al. (2005) demonstrated that it distinguishes the strata above bedrock in detail taking Pulheim Area as an example. In different areas, much work was done to verify the accuracy of joint inversion (Picozzi and Albarello 2007; Garcia-Jerez et al. 2007; Parolai et al. 2005; Castellaro 2016). However, most research did not identify the weathered strata which are important to civil safety and development such as excavatability assessment, foundation design, and slope stability.

In this study, it develops another observation array to collect microtremor signal. It deploys small scale array in the traditional microtremor observation array. Then, SPAC is applied to extract dispersion curve. The inversion of dispersion curve is done with the genetic algorithm. We collected microtremor array data at 50 sites in Jimo, Shandong Province, China. The 1D S-wave velocity structure is achieved at each site. By using small scale observation, it identifies different strata including weathered strata in detail. In order to test the accuracy of inversion result, 5 sites are chosen to drill according to the researching area size. Comparison between inversion results and boreholes, it shows agreement with each other. At last, the S-wave velocity structures in different depths above the fresh bedrock are plotted.

Geological setting

Jimo, China, is located at the eastern edge of the Jiaolai Basin and the Sulu Orogenic Belt. It has undergone multiple stages of tectonic movements in different ways. Since Mesozoic, the tectonic activity has become strong. It develops Mesozoic strata such as Laiyang Formation and Qingshan Formation. The major lithology includes sandstone, conglomerate, mudstone, and intermediate-basic volcanic rock. The magmatic activity was also intense in the Mesozoic. Due to the developed faults, large amount of magma intruded along the fault zone to the upper crust or ejected from the surface. Magmatic rocks are widely distributed at the surface and within the upper crust and exhibit variable degrees of weathering.

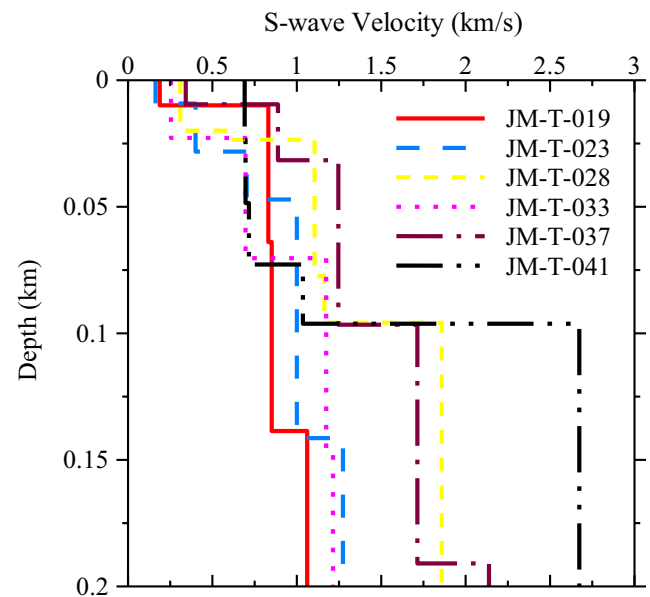
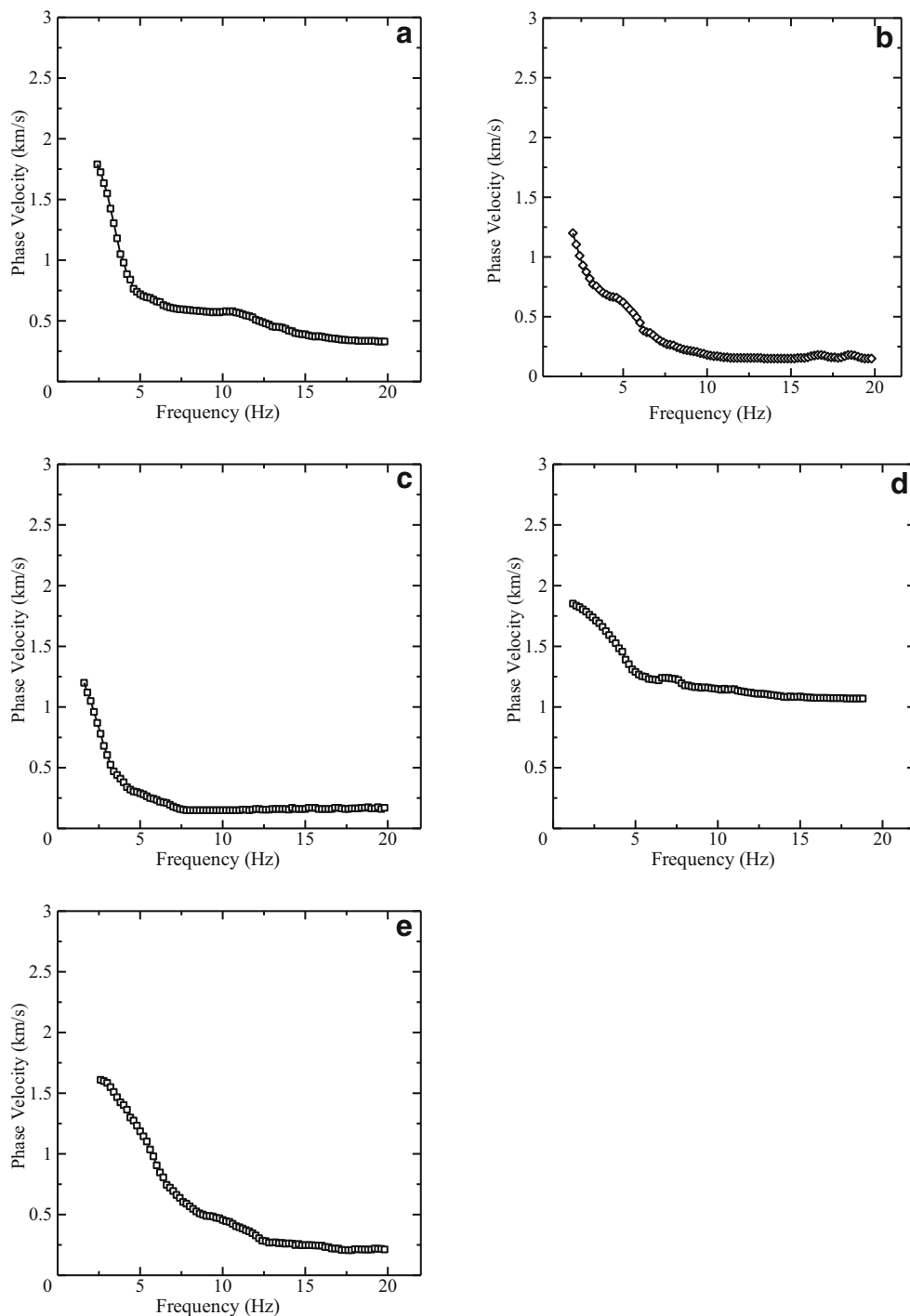


Fig. 4 Inversion results of different sites (Part)

Fig. 5 Dispersion curves of the 5 test sites. **a** The curve of borehole 1. **b** The curve of borehole 2. **c** The curve of borehole 3. **d** The curve of borehole 4. **e** The curve of borehole 5



Method and data acquisition

Usually, the frequency-wavenumber method (F-K, Capon 1969) and the SPAC method (Aki 1957) are used to extract dispersion curve from the microtremor signal. F-K method is more flexible because it involves an irregular array. But it needs large number of observation stations. SPAC method is the popular method. It requires arranging an observation station at the center of a circle and three observation stations on

the circumference to form a regular triangle (Okada 2003; Asten 2006; Cho et al. 2004, 2008; Asten and Hayashi 2018). In this paper, SPAC method is chosen to deal with the field data.

SPAC method bases on the assumption that the microtremor signal is stationary and random in time and space field. The key step is to calculate the SPAC coefficient of two stations. It is expressed as the following equation (Okada 2003, 2006):

Table 1 Inversion results of 5 test sites. At the same time, it gives the inferring strata

No.	Vs (km/s)	Thickness (m)	Depth (m)	Strata
A: site borehole 1				
1	0.300	9.5	9.5	Quaternary sediments/silt
2	0.500	4.6	14.1	Highly weathered stratum/sandstone
3	0.700	56.4	70.4	Moderately weathered stratum
4	1.092	–	–	Fresh bedrock
B: site borehole 2				
1	0.160	9.5	9.5	Quaternary sediments/clay
2	0.400	6.1	15.6	Highly weathered stratum/sandstone
3	0.755	19.0	34.6	Moderately weathered stratum
4	1.000	–	–	Fresh bedrock
C: site borehole 3				
1	0.182	17.0	17.0	Quaternary sediments/clay
2	0.475	12.4	29.4	Highly weathered stratum/sandstone
3	0.716	57.5	86.9	Moderately weathered stratum
4	1.066	–	–	Fresh bedrock/granite
D: site borehole 4				
1	0.884	10.5	10.5	Slightly weathered stratum
2	1.200	56.3	66.8	Fresh bedrock/granite
3	1.444	–	–	–
E: site borehole 5				
1	0.207	9.0	9.0	Quaternary sediments/silt
2	0.896	8.9	17.9	Slightly weathered stratum
3	1.086	10.1	28.0	Fresh bedrock/granite
4	1.270	–	–	–

$$\rho(\omega, r) = \frac{1}{2\pi\phi(r = \omega, 0, 0)} \int_0^{2\pi} \phi(\omega, r, \theta) d\theta \tag{1}$$

where $\rho(\omega, r)$ is the SPAC coefficient, $\phi(\omega, r, \theta)$ is the function of space autocorrelation, r is the distance between two stations, θ is the azimuth, and ω is the angular frequency.

The SPAC coefficient for regular triangle observation array can also be expressed as follows:

$$\rho(\omega, r) = J_0\left(\frac{\omega r}{c(\omega)}\right) \tag{2}$$

where J_0 is the Bessel function of the first kind zero-order, $c(\omega)$ is the phase velocity of the frequency ω in the distance of r .

Also, $\omega = 2\pi f$, f is the frequency. So when given the frequency f , the phase velocity c is a single-valued function of the distance r . Using this principle, the phase velocity c can be achieved by fitting with the first kind zero-order Bessel function.

Based on traditional observation array, we added a small scale regular triangle observation array in the center (Fig. 1) in order to identify the weathered strata above fresh bedrock. According to the proof of miniature array, it is effective to

improve the accuracy of microtremor survey method in theory (Cho et al. 2013).

Using this revised observation array, we collected microtremor signal at 50 sites. The instrumentations are vertical-component MTKV-1C seismometers and Datamark LS-8800 data loggers. The sampling frequency is 100 Hz and the magnification is 16. We visited each site for 30 min of continuous data recording.

Data processing

According to the basic theory of microtremor, we processed the entire recorded microtremor signal. Firstly, the SPAC coefficients were calculated between every two observation stations. In the observation array, the SPAC coefficients were calculated between the same distance stations. Then, the curves of average coefficient of all station pairs with the same space distance are achieved which are used to extract the dispersion curves. Figure 2 shows an example of SPAC coefficient that the distances between two stations are same in this observation array. The last picture is the result of average coefficient of all these station pairs.

After calculating the SPAC coefficient, it is used to fit the Bessel function. Hence, the dispersion curve of every survey



Fig. 6 Samples of different depths of the 5 boreholes. **a** Samples of borehole 1. **b** Samples of borehole 2. **c** Samples of borehole 3. **d** Samples of borehole 4. **e** Samples of borehole 5. Depths of the samples

are labeled at the corner of every picture. The number labeled at the corner of every picture represents the depths of the samples

points is achieved. Figure 3 shows part of dispersion curves of the research area. Then we applied the genetic algorithm to inverse the 1D S-wave velocity structures above the fresh

bedrock at each site. In this process, we set an initial model for inversion according to the known geological materials. Figure 4 depicts several inversion results of different sites.

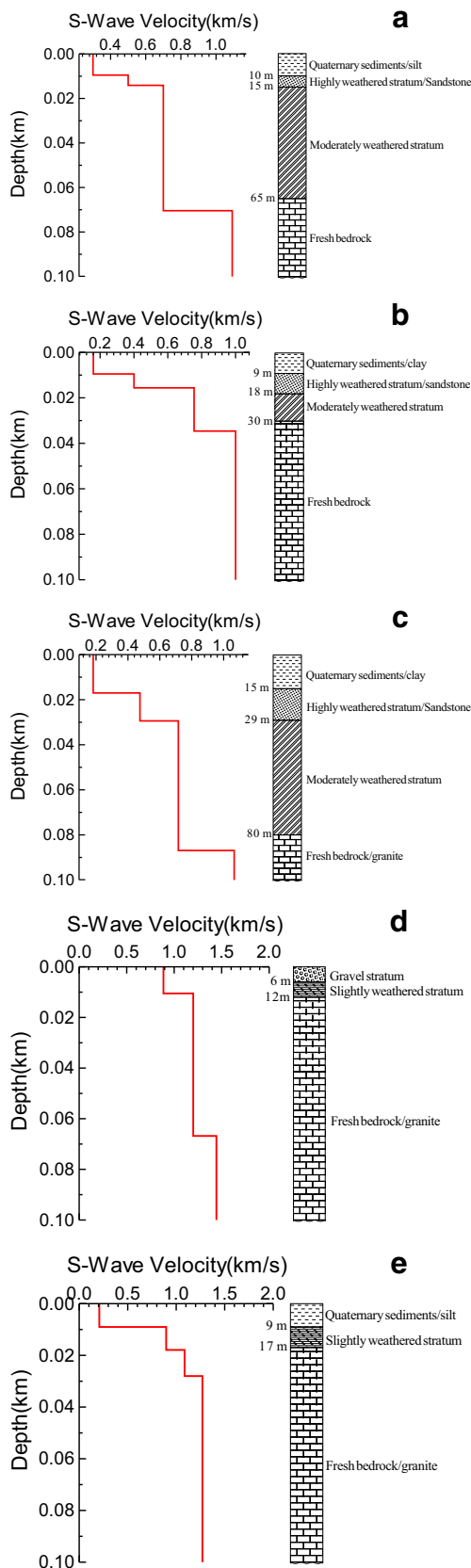


Fig. 7 Comparison between inversion S-wave velocity structures and drilling materials

Using this revised observation array, the band of frequency can be extended especially the part of high frequency. In this research field, it gets the results from 13 to 20 Hz which are critical to improve the resolution of the shallow ground.

Discussion

After processing all the microtremor data, we chose 5 sites to verify the results of small scale observation array survey comparing with borehole materials. The dispersion curves and inversion results of microtremor survey method are shown in Fig. 5 and Table 1. In Table 1, we infer the different layers to corresponding strata with inversion S-wave velocity according to the geological conditions of this area. In the same layer, it may be inferred as different rock because they belong to the same ranges of S-wave velocity.

In the 5 sites, drillings were deployed. All boreholes were conducted downing to the depth of fresh bedrock. The S-wave velocity profiles which were derived from microtremor array measurements are in a good agreement with well logs data. Figure 6, it shows the samples of different depths of the 5 boreholes. Comparison with the inferring strata, most of the results are consistent. In Fig. 7, the inversion S-wave velocity structures are compared with drillings. According to the results of inversion and drilling, we are sure that this method is dependable to map the shallow S-wave velocity structures above the fresh bedrock. Especially, it can determine the weathered strata which are critical to engineering construction.

Using the results of all measured sites' S-wave velocity profiles inferred in this study, we mapped the S-wave velocity in different depths for this research area. For the same depth, all the S-wave velocities are known, the plan is plotted using Surfer Software. Several maps are shown in Fig. 8. According to the geological condition, most areas are intruded by magma. From the Fig. 8, it shows that the low velocity almost in the same areas which results from weathered strata. The degree of weathered leads to the relatively low velocity in different depths. It provides the weathered trend in different depths. In the deep layer, the weathered degree becomes uneven. In the depths of 80 m and 100 m, there are parts of fresh bedrock in the middle of this research area. This result provides the critical information about S-wave velocity and distribution of weathered strata in different depths.

Conclusions

The objective of this study is to estimate the S-wave velocity structure above the fresh bedrock especially the weathered strata which widely spread in most areas. It launches a revised observation array to record microtremor signal. In the

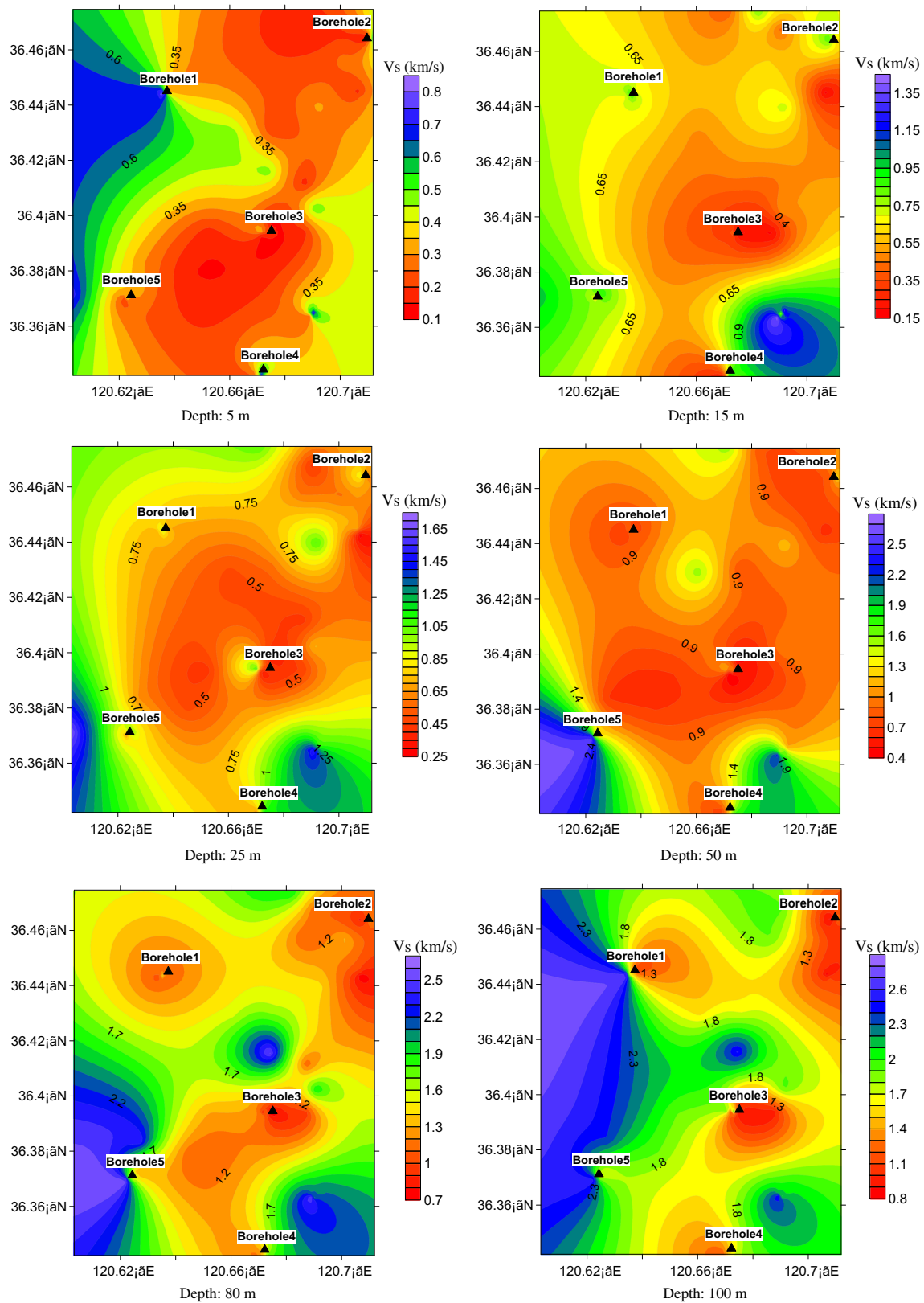


Fig. 8 S-wave velocity of different depths including 5 m, 15 m, 25 m, 50 m, 80 m, and 100 m. The X-axis represents longitude and the Y-axis represents latitude. Different colors represent S-wave velocity

traditional observation array, it adds a small scale array to improve the resolution and survey accuracy especially the identification of weathered strata.

To verify the effectiveness of this revised observation array, this study performed microtremor field observation in Jimo, China. The shallow structures downing to the fresh bedrock were estimated successfully for all the microtremor survey sites. To validate the S-wave velocity and thickness obtained from the microtremor array measurements, 5 boreholes were drilled. The results show a good agreement with well logs data in the 5 test sites. According to the borehole materials, the corresponding S-wave velocity of fresh bedrock is above 1000 m/s. It successfully identified the weathered strata. The S-wave velocity of high-weathered strata is 300–500 m/s, the S-wave velocity of middle-weathered strata is 500–800 m/s, and the S-wave velocity of weak-weathered strata is 800–1000 m/s. Using the exploration results of all sites, it depicted the S-wave velocity in different depths of Jimo area. This field example verified the effectiveness of revised observation array. It provides important information above the fresh bedrock such as the weathered degree of magma strata, the depth of fresh bedrock, and S-wave velocity in different depths.

In order to make sure this method can be used with more confidence in engineering construction, the survey results need further validation. In this paper, we just considered the surface wave as fundamental mode. For further research, it can take into account the multimode to improve the probing precision of shallow ground.

Acknowledgments The authors would like to express gratitude for Dr. Louis N.Y. Wong and all anonymous reviewers for their valuable comments and suggestions that greatly improved this paper.

Funding information This research was supported by the National Key R&D Program of China (2019YFB1504101) and the National Major Project of China (2017ZX05008-007).

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