18th International Conference on Structural Mechanics in Reactor Technology (SMiRT 18)
Beijing, China, August 7-12, 2005
SMiRT18-K03-2

DISTRIBUTION OF BASE ROCK DEPTH ESTIMATED FROM RAYLEIGH WAVE MEASUREMENT BY FORCED VIBRATION TESTS

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ABSTRACT

This paper shows an application of Rayleigh wave methods to a real site, which was performed to determine spatial distribution of base rock depth from the ground surface.

At a certain site in Sagami Plain in Japan, the base rock depth from surface is assumed to be distributed up to 10m according to boring investigation. Possible accuracy of the base rock depth distribution has been needed for the pile design and construction. In order to measure Rayleigh wave phase velocity, forced vibration tests were conducted with a 500N vertical shaker and linear arrays of three vertical sensors situated at several points in two zones around the edges of the site. Then, inversion analysis was carried out for soil profile by genetic algorithm, simulating measured Rayleigh wave phase velocity with the computed counterpart.

Distribution of the base rock depth inverted from the analysis was consistent with the roughly estimated inclination of the base rock obtained from the boring tests, that is, the base rock is shallow around edge of the site and gradually inclines towards the center of the site. By the inversion analysis, the depth of base rock was determined as from 5m to 6m in the edge of the site, 10m in the center of the site. The determined distribution of the base rock depth by this method showed good agreement on most of the points where boring investigation were performed.

As a result, it was confirmed that the forced vibration tests on the ground by Rayleigh wave methods can be useful as the practical technique for estimating surface soil profiles to a depth of up to 10m.

Keywords: Rayleigh wave method, forced vibration test, linear array, genetic algorithm, inversion analysis

1. INTRODUCTION

Before constructing a large-scale building or structure, it is important to evaluate the spatial distribution of base rock depth and ground profiles accurately as possible for detailed pile head design and drilling length estimation. Methods for investigating the ground profiles include the boring investigation, PS logging, reflection method, refraction method and elastic wave exploration etc., although most of these investigation methods should be carried out on a large scale and relatively expensive.

Recently, Rayleigh methods have often come to be used for investigating ground profiles, that make use of the dispersive characteristics of Rayleigh waves observed in microtremor or forced vibration test on ground surface. These methods are performing well as a technique to assume ground motion characteristics in the field of simulating seismic motion. These investigation can be made without drilling any boreholes, which means that considerable number of tests can be performed at several points in a short time with minimal cost. Therefore, Rayleigh wave methods are available for supplementing the result of boring investigation spatially, for example, when the spatial distribution of ground profile is demanded in the whole area of a site.

This paper shows a case study about application of the Rayleigh wave velocity inversion based on forced vibration tests. In the site, the distribution of the base rock depth was preliminarily estimated from boring investigation, and assumed to be around 10m below the ground surface. These investigations were performed to assume spatial distribution of the base rock depth from the surface. The estimated ground profile is compared with the base rock depth obtained from drilling work for driving piles, and then its accuracy and distinctive trend are evaluated.

2. RAYLEIGH WAVE METHOD

2.1 Overview

For the purpose of assuming ground profiles, popular methods which belong to vibration measurement investigation include the boring investigation, reflection method, refraction method and elastic wave exploration etc. These methods are effective for the investigation of deep ground structures required for the simulation of long periodic seismic motion, including their spatial distribution from epicenter to the intended site and the ground profiles just beneath the site. Effectiveness of these methods is shown in a considerable number of studies, especially in the field of estimating seismic motion.

Recently, in order to assume ground structures, such an easy-to-use method that makes use of vibration measurement are coming into wide use for the convenience and inexpensiveness (e.g. Tokimatsu et al., 1992). Most of these methods are employing the dispersive characteristics of surface wave observed in records on ground surface. Specifically, that is a kind of optimization technique to identify the soil profile which changes the parameters of soil profile to adopt the calculated dispersion curve of Rayleigh wave into observed one. Especially, in the case the dispersion characteristics is required for deep ground; above seismic bedrock, technique to obtain the dispersion curve of Rayleigh wave includes spatial autocorrelation (SPAC) method or frequency-wave number (F-K) spectrum method, making use of microtremor observation on real site.

2.2 Applications to shallow ground estimation

On the other hand, it seems feasible to adopt such an easy-to-use method to the estimation of the ground profiles in a shallow ground, where base rock depth is needed for the design of foundations of structures. In constructing a large-scale structure, spatial distribution of the site could not be considered to be consistent in general, as a result that the area of such site must be relatively commodious. Therefore, the progress of easy-to-use method is strongly expected for investigating shallow ground profile. When base rock depth is shallow, boring investigation is easier compared with the cases when the base rock is deep. In the situation when a large structure is planned in a commodious site, however, considerable amount of boring tests should be performed, in order to assume spatial distribution of the base rock depth required for designing basement structure. An easy-to-use method using surface ground measurement can be convenient in such a case, not only because the tests on considerable number of points can be performed in a short time but because the tests can be performed economically.

Let us turn to the discussion of excitation source. In the case that base rock depth is shallow, microtremor measurement follows some technique for data processing (e.g. Park et al., 1999), with the aim of raising accuracy of observed dispersion curves. The major reason is that the amplitude of the microtremor in higher frequency is not sufficient to be observed in such case.

On the other hand, an active method in which artificial excitation on the ground caused by a shaker or a maul can be effective when the base rock depth is shallow. The reason for the expectation is improve its coherence and raising accuracy, while the methods appeared earlier than microtremor measurement. It also looks favorable that not so big excitation force be required, because the intended ground is shallow and need less energy to shake.

3. FORCED VIBRATION TEST

In this section, we will report a case study about application of the Rayleigh wave velocity inversion based on forced vibration tests. The estimated ground profile is compared with the base rock depth obtained from drilling work for driving piles.

3.1 Test Site

Figure 1 shows the sketch map of the site. The test site of this study is located in the east end of Sagami-Plain, Japan. According to visual observation on the ground surface, the site is surround by outcrops. According to the boring investigation tests on a number of points at the site, the base rock is supposed to slope down from the edge to the center of the site. The maximum depth of the base lock is considered to be about 30m. On the valley of the base rock, loam layer (i.e. Kanto Loam Layer) is supposed to be heaped up.

Especially in the outer edge of the site, the base rock depth is generally estimated from the ground surface to a depth of 10m. Accordingly, accurate depth of the base rock distribution has been needed for the design of short piles and their construction. Due to the high demand mentioned above, forced vibration tests on the site were conducted. A vertical shaker and linear measurement array composed of several points were set in two areas of the site. Then, inversion analysis by using genetic algorithm was carried out to compare the computed phase velocity of Rayleigh wave with that of observed results.

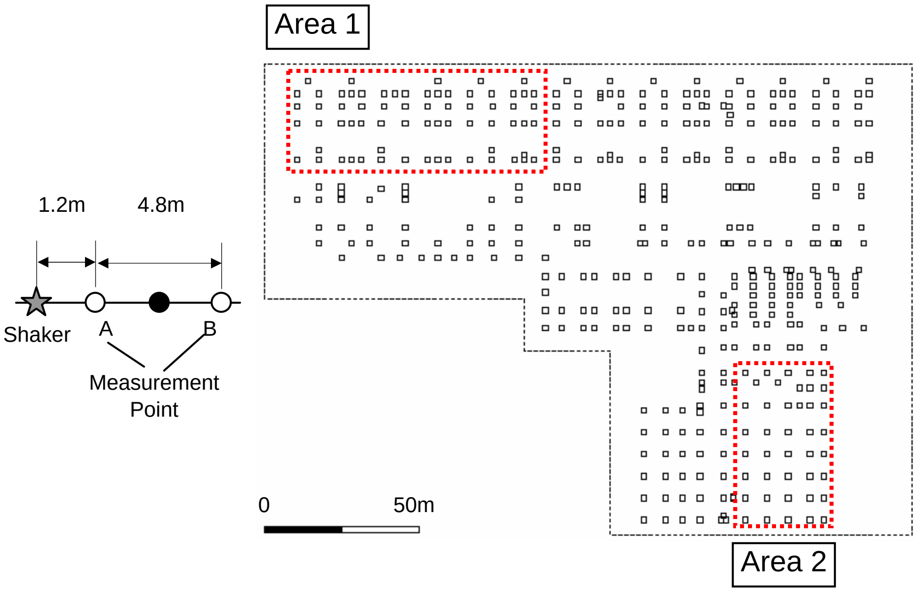


Fig.1 Planimetric map of the site

3.2 Procedure of excitation and measurement

Two areas were selected in the site to estimate the base rock depth: Area 1 and Area 2. A 500N shaker was set in a prescribed point on the ground surface, and it was shook vertically. Sweep excitation was chosen as the input pattern, and the frequency was set to varied from 5Hz up to 100Hz. Figure 1 also shows the pattern of the linear array observation. A shaker and measuring points were set along the line. In order to evaluate horizontal propagation velocity, vertical acceleration was observed on two points across the target point. Eleven target points were set in Area1, and six points in Area2. Servo-type accelerometer SPC-51 was used for the measurement, and data for the periods of 100 seconds was recorded on each shake.

3.3 Procedure of inversion analysis

3.3.1 Dispersion curves from measured acceleration

As the first step, measured dispersion curves of Rayleigh wave were assumed from the acceleration records obtained from the forced vibration tests. Detailed procedures are shown as follows:

1) For all the measured data, calculate the transfer function between two measuring points, near the excitation point and the other one.

2) Based on the phase difference $\phi(f)$ of transfer function, obtain the relationship between frequency f (Hz) and phase velocity v (m/s) by the following equation.

$$v = \frac{2\pi l f}{\phi} \tag{1}$$

Where, l is the distance between accelerometers (4.6m)

The range of phase velocity v given by the Eq.1 should be between $2l$ to $4l$, so as to avoid spatial aliasing of processing time history data. By the preliminary shaking test and measurement with vertical and longitudinal component, particle motion orbits on a vertical plane along observation lines were verified. Since they have reverse and oval shape between 5 Hz and 30Hz, we considered that the observed acceleration in the frequency range be composed chiefly of fundamental mode of Rayleigh wave.

3.3.2 Inversion analysis for estimation

For the second step, ground profiles were assumed by comparing observed dispersion curves with calculated ones. The calculated dispersion curve was derived from the generalized transfer and reflection matrix method proposed by Luco and Apsel (1983).

The procedure of the inversion analysis is to identify the parameters that can minimize residual of dispersion curve, defined as follows.

$$S = \sum_{i=1}^{N} (P_{oi} - P_{ti}) \tag{2}$$

Where, S is the residual, P_{oi} and P_{ti} are the phase velocities of the i th point of frequency f from observation and calculation, respectively. N is the total number of the point of frequency. Based on the preliminary verification mentioned above, first mode of Rayleigh wave is used for P_{ti}. The intended frequency range was between 5 Hz and 30 Hz.

Based on the results of boring investigation at the site, it is likely that the base rock is composed of tuff sand stone of tertiary deposit, and the loam is deposited on the base. Therefore, one-layer model was used as initial soil profiles for the inversion analysis. For each layer, S-wave velocity (Vs) and the thickness of layer were selected for search parameters, and mass density and P-wave velocity (Vp) were kept constant. Since the ground is almost flat in the whole area, surface level is used as a reference for showing the base rock depth below.

Genetic algorithm (GA) was used as an inversion method of minimizing the residual: Eq.2. Values for each GA parameters are as follows; 1 for the trial number of times, 5 for the number of generation, 10 for the number of individuals and 0.9 for the probability of cross over. Event of mutation or choice of elite was not employed in the analysis.

Table 1 Initial model of ground profile and search range of parameters

Layer Number	Thickness (m)	Density (Mg/m^3)	Vs (m/s)	Vp (m/s)
1	16 1	1500	240 160	450
Base Rock	-	2250	2025 675	3480

Note	240	Upper limit of range for search
	160	Lower limit of range for search

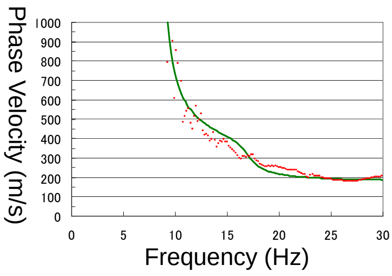
4. ESTIMATED RESULTS

Figure 2 shows the calculated dispersion curves obtained by the inversion analysis as well as observed results. Moreover, Figure 3 indicates assumed profiles of Vs by the inversion analysis.

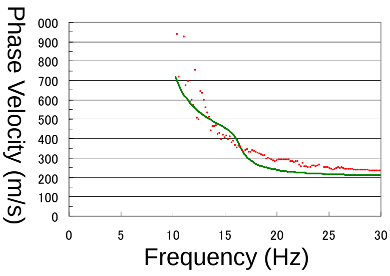
Based on the inverted Vs profiles, the base rock depth was assumed considering the engineering bedrock; where Vs is larger than 400 m/s, as base rock layer. Figure 4 shows the distribution of assumed base rock depth. In the figure, contour map of base rock depth by actual measurement is also indicated, that is measured from reactive torque profiling of drilling. The depth of drill tip is supposed to reach deeper than the base rock depth, on the grounds that the drill tip seems to be inserted to base rock while drilling work. At the point 2C, base rock depth obtained by the boring investigation was 8m, and the assumed depth of the drill tip was 14m. Accordingly, 6m is uniformly subtracted from the depth of the drill tip in order to get actual base rock depth shown in Figure 4.

In the Area 1, assumed base rock depth from Rayleigh wave method is about 6m in line A, and the surface of the base rock gradually inclines towards the point 2D. In the point 2D, the depth is assumed to be 10.7m, therefore the base rock is supposed to be locally depressed. On the other hand, base rock around Area1 distributes between the depth of 7m and 9m, according to the actual measurement. It can be pointed out that the base rock spreads like a mountain ridge across the length of line 2. As mentioned above, assumed base rock depth from Rayleigh wave method differ less than 2m from the actual measurement, however, both give close agreement in a large sense.

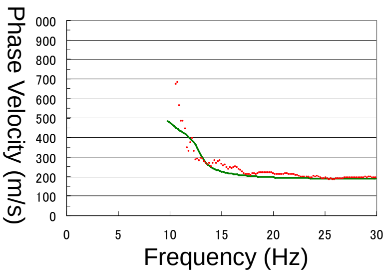
As for Area 2, assumed base rock depth from Rayleigh wave method is about 6m or 7m near the points 5J and 6J. Meanwhile it is rapidly deepened at around the points 5K, 5L and 6I, and the depth is supposed to be between 11m and 12m. When the assumed base rock depth is compared to that from the actual measurement, the assumed base rock depth gives good agreement with measured depth around the points 5J and 6J. However, their differences are rather large around the point 6I where the inclination of the base rock is steep.



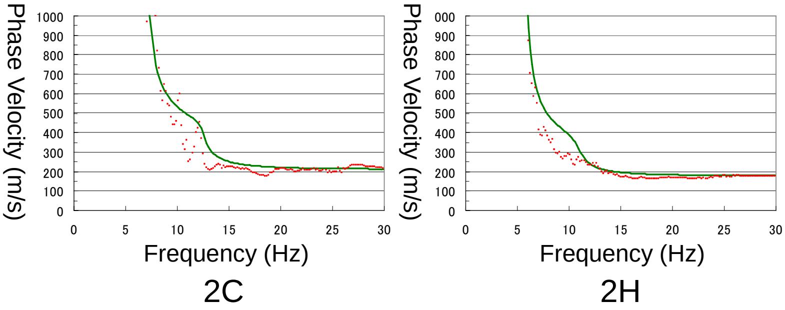
4A



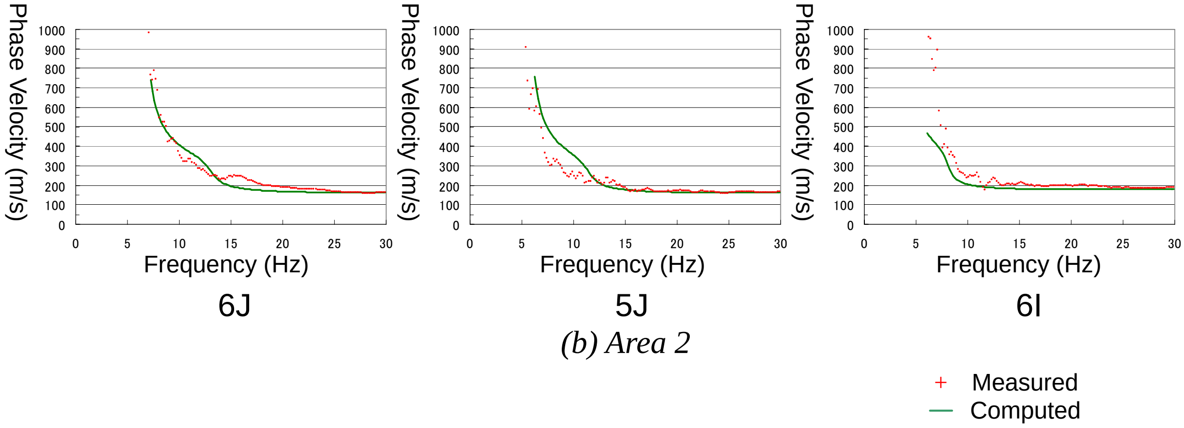
2A



1F

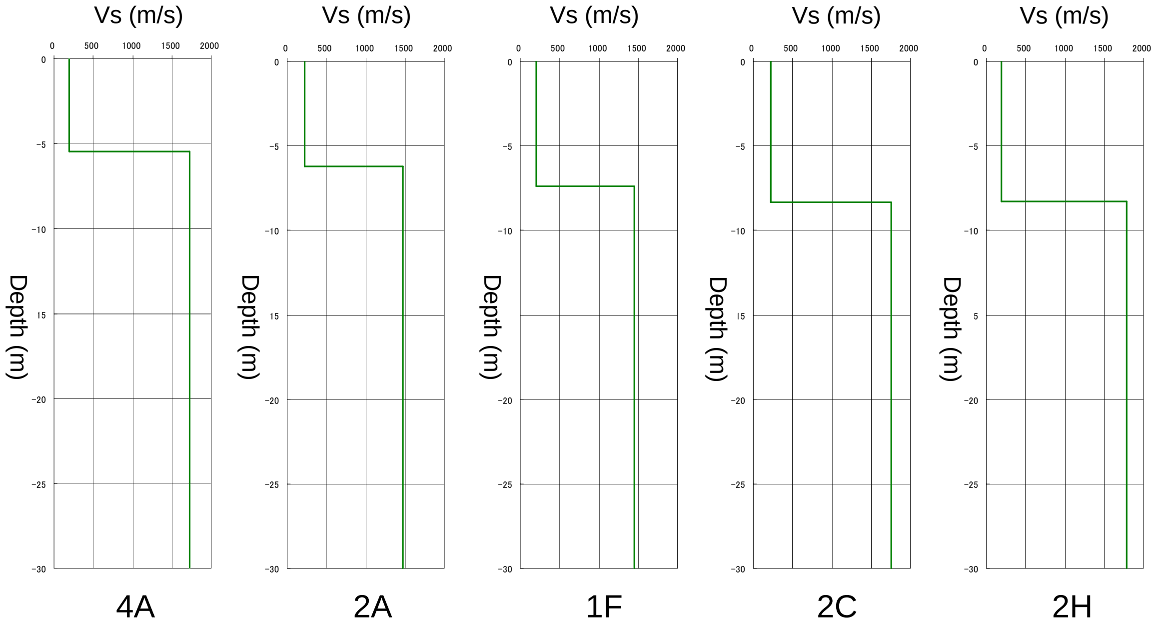


(a) Area 1

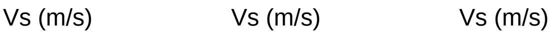


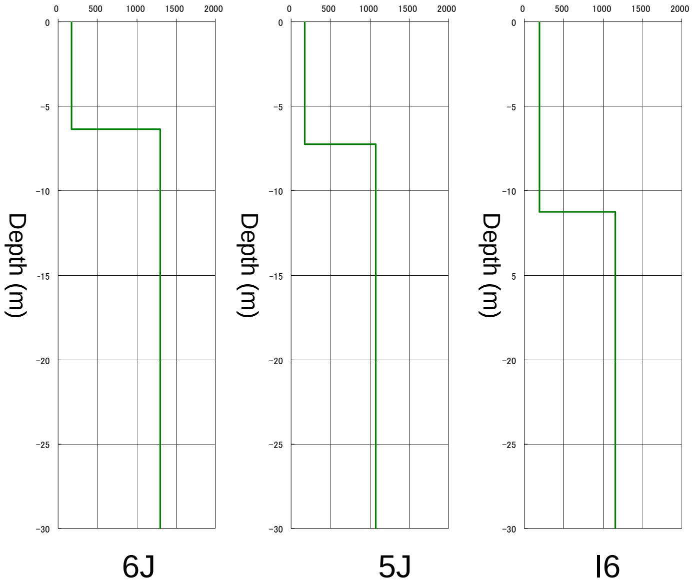
(b) Area 2

Fig.2 Calculated dispersion curve obtained by the inversion analysis



(a) Area 1

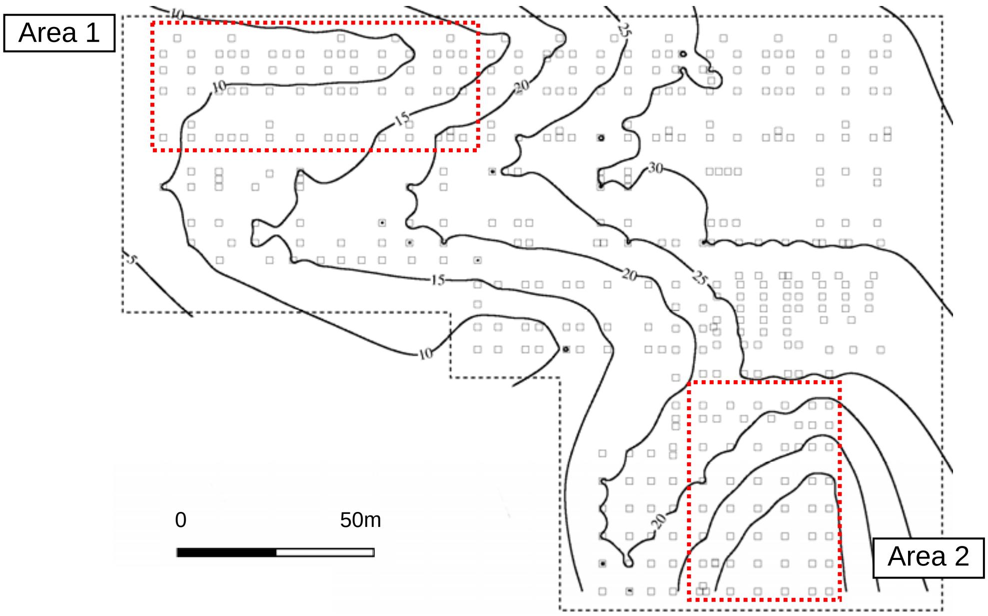




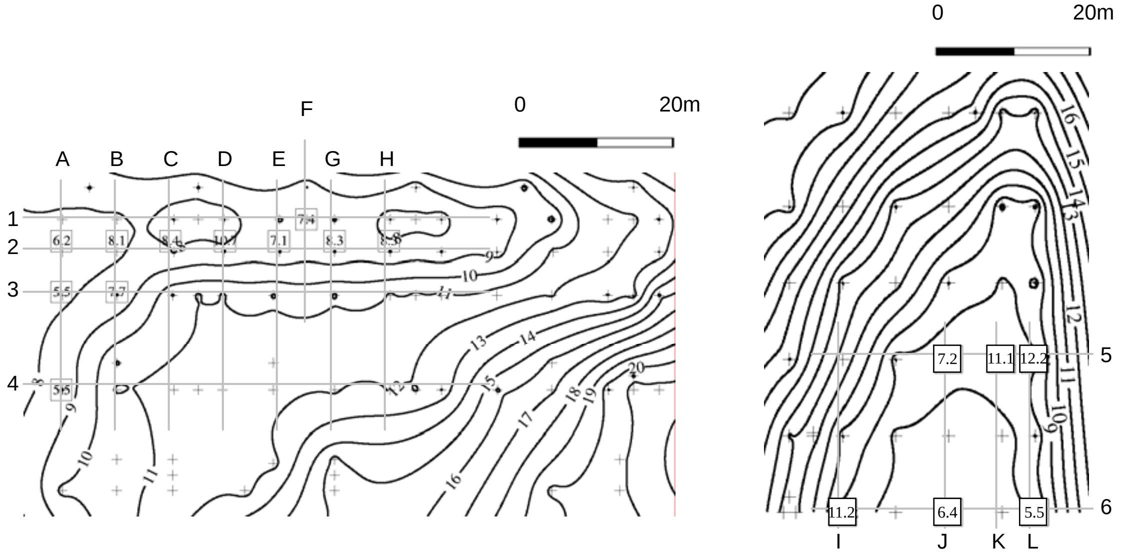
(b) Area 2

Fig.3 Assumed profiles of Vs by the inversion analysis

Some reasons for the difference are supposable. One reason is that assumed ground structures from the inversion analysis give an averaged ground profile on the intended point. This is due to the Rayleigh wave method based on the hypothesis of the parallel-stratified ground. Another reason is that single layer model for the surface ground were used in the whole site, in spite of the influence of weathered tuff sandstone is not apparent. The determined distribution of the base rock depth by this method showed good agreement on most of the points where boring tests and drilling were performed, except for a few points assumed to be influenced by a sudden inclination of the base rock or an existence of weathered rock stratum beneath the target point.



(a) Whole Area



(b) Area 1

(c) Area 2

Regend 6.2 Base rock depth (m) from inversion analysis

─ 10 ─ Base rock depth (m) from drilling work

Fig.4 Assumed base rock depth

5. CONCLUSIONS

For the purpose of measuring phase velocity of Rayleigh wave, forced vibration tests by a vertical shaker and linear array were conducted in a certain site. Then, inversion analysis by genetic algorithm was carried out, so as to adopt the computed phase velocity of Rayleigh wave to that of observed results. Consequently, base rock depth had been supposed to be shallow around the edges of the site and to increase gradually towards the center of the site. By the inversion analysis, the base rock depth was evaluated as 5m to 6m around the edges and 10m in the center of the site.

Evaluated distribution of base rock depth showed good agreement with boring tests at most of the drilling points; however, there are a few points of poor agreement where sudden inclination of base rock or existence of weathered rock stratum beneath the point can be considered. As a result, it was confirmed that Rayleigh wave methods by the forced vibration tests on the ground surface could be useful as a practical technique for estimating shallow surface soil profiles to a depth of around 10m.

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