# BURIED CHANNEL DELINEATION USING A PASSIVE SURFACE-WAVE METHOD IN URBAN AREA

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## Abstract

A passive surface wave method has been applied to delineate buried channels in urban area of Japan. S-wave velocity structure down to 100m is very important in the local site effect of strong ground motion caused by earthquake. Especially, the buried channels filled with alluvial deposits intensify seismic waves and cause strong ground shaking. We have tried to delineate three-dimensional S-wave velocity structure down to 100m on the basis of the passive surface wave method. The test site is in Soka city, Saitama prefecture, Japan and the size of the site is about 3 km square. Sixty-two passive surface wave methods were carried out to delineate buried channels filled with alluvial deposits, which is embedded about 50m beneath surface of this area. Array size is about 50 to 100m and triangular or L shaped arrays with 10 or 11 receivers were deployed. A spatial auto correlation method was applied to the approximately ten minutes vertical component of micro-tremors data. Phase velocity curves were calculated in the frequency range of between 2 and 10 Hz. Fundamental mode of phase-velocity curves are clearly obtained in all observation points. A one dimensional inversion using a non-linear least square method has been applied to the phase-velocity curves and one-dimensional S-wave velocity structures were obtained. The resultant one-dimensional structures were interpolated into a three-dimensional structure. We succeeded to map the shape of buried channel and the depths of the channel agree very well with the borehole data.

## Introduction

After the 1995 Hanshin earthquake, Japanese seismology has been greatly developed by a considerable number of studies. It enables us to predict the strong ground motion of future earthquakes with high accuracy. The surface ground motion of natural earthquakes is generally represented as the convolution of three characters, such as 1) source characteristics, 2) propagation path effects and 3) local site effects.

Over the last decade, a large number of studies have been made on the source characteristics, such as active fault characteristics and rupture processes. Active fault survey has revealed the activity and cycle of each fault. Geophysical exploration methods, such as seismic reflection, and fault trenching have played important roll in such progress. Observed strong ground motion data revealed the rupture process of large earthquakes. A nation-wide network of strong motion seismometers, which is called K-NET and KiK-net has provided valuable observation data to researchers.

The understanding of propagation path effects has also progressed in the last decade. It has been established that the effect of two- or three- dimensional S-wave velocity structure has large effect on the earthquake damage. Three-dimensional P- and S-wave velocity structure of sedimentary basin has been constructed and it has made possible three-dimensional simulation of natural earthquakes. The geophysical exploration methods and the network of strong motion seismometers have also played important roll in such progress.

All these things make it clear that the new observation method, such as the geophysical exploration methods and the nation-wide network of seismometers, cause the progress in the source characteristics and the propagation path effects.

However, only few attempts have so far been made at new observation methods for evaluating the local site effects in the last decades. A great deal of effort has been made on the collection of existing borehole data in the local site effects evaluation. What seems to be lacking, however, is the development of new non-destructive observation method for near-surface velocity structures. For example, almost existing borehole data has only blow count (N-value) and no S-wave velocity that is most important for the local site effects. Considering that the understanding of the source characteristics and the propagation path effects has progressed with new observation data, the understanding of local site effects can also progress with the new observation data in near-surface region. Therefore, we have started the development of new exploration method which can be used for estimating S-wave velocity structures down to the depth of 100m from the surface.

## A Passive Surface-wave Method

The authors have developed a multi-channel and multi-shot surface wave (Rayleigh wave) method using active sources and applied it to engineering and environmental problems such as river banks, reclaimed lands and housing sites (Hayashi and Suzuki, 2004). The penetration depth of the surface wave method is about 10m using a sledge hammer as a source and 20m using a weight drop. There is fairly general agreement that the S-wave velocity model down to the depth of 30m is important for evaluating the local site effect of strong ground motion. The penetration depth of the surface wave method with active sources is not enough for the local site effect evaluation. Larger sources and longer survey line are required for increasing penetration depth in the surface wave method. However, the larger source and longer survey line decrease simplicity of the survey and increase survey cost. Therefore, we started to develop alternative method.

The Earth's surface is always vibrating weakly. This vibration is called as micro-tremors. The micro-tremors are generated by the various sources, such as winds, ocean waves at the seashore, traffic noises, heavy machinery factories and household appliances. Because the micro-tremors are generated by sources on the ground surface, the micro-tremors mainly consist of surface-waves, and the vertical component of the micro-tremors can be considers as Rayleigh waves. Therefore, it is reasonable that the dispersion curve of the vertical component of the micro-tremors is the dispersion curve of Raylegh waves. Micro-tremors consist of wide frequency range of surface waves from the period of 0.1 second to 10 seconds. Therefore, S-wave velocity model down to several kilometers can be obtained using passive surface-waves.

Okada (2003) has developed a large scale passive surface wave method, so called a micro-tremors array measurements, using long period micro-tremors. The penetration depth of the method is from 100m to several kilometers. We have employed the Okada's method and applied it to shallower problems, such as geo-technical, environmental and earthquake engineering. Our depth of interests is from several ten meters to 100m. Henceforth, we use the term "passive surface wave method" to refer to the micro-tremors array measurements for shallower surveys. Unlike the active surface wave methods, the passive method does not need any sources and needs two-dimensional arrays, such as triangles, circles or crosses. Because the sources of the micro-tremors are distributed randomly in space, the micro-tremors do not have any specific propagation directions. Therefore, two dimensional arrays are required for calculating the phase-velocity of micro-tremors.

## Outline of Test Site

In order to evaluate the applicability and reliability of the passive surface wave method in urban area, we have applied the method to S-wave velocity structure survey in a suburb of Tokyo, Japan.

The test site is in Soka city, Saitama prefecture, Japan. The size of the site is about 3 km square. The site is placed in the Nakagawa Lowland area and topography is almost flat. AIST (National Institute of Advanced Industrial Science and Technology) has collected existing boring data in the site and approximate geological condition has been already known (Ishihara et al., 2004). A suspension PS-logging has been carried out in a borehole in the test site as well.

Figure 1 shows the location of boreholes and the depth of alluvium estimated from the borehole data. The test site consists of buried channels and buried terraces. The depth (thickness of alluvium) of channels is about 50m and one of terraces is about 15m. Figure 1 shows that the Soka Park, placed at the center of the test site, is on the buried terrace. It is clear that a deep buried channel exists in south-east side of the Soka Park. However, the boundary of the channel and the terrace winds unnaturally in south of the park (A). In east side (B) and north side (C) of the park, the boundary cannot be determined due to the lack of borehole data.

The main purpose of the passive surface wave method is the delineation of buried channels and terraces. Data acquisition was carried out at 62 points in the test site. Figure 2 shows the location of data acquisition points.

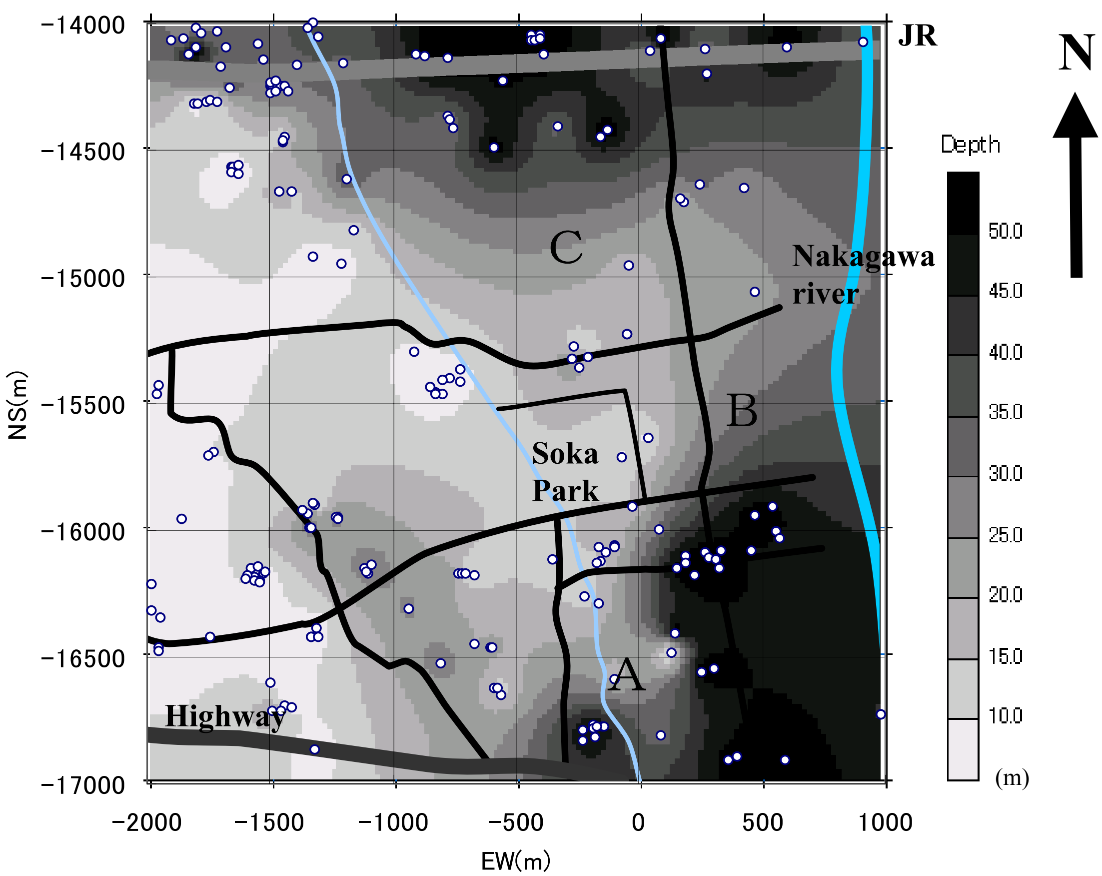


**Figure 1.**: Location of existing boreholes (white circles) estimated depth of alluvium.

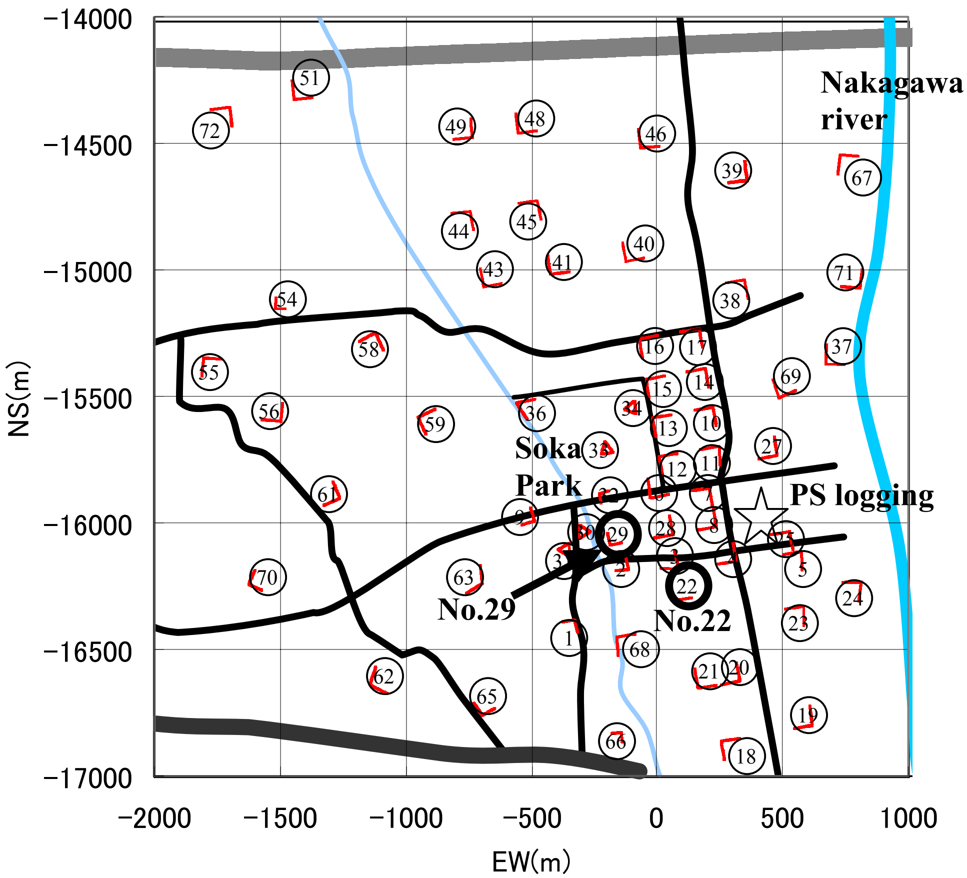


**Figure 2.**: Data acquisition points and array shape.

## Data Acquisition and Analysis

Geophones that have the natural frequency of 2 Hz are used as receivers and an OYO McSEIS-SXW is used for data acquisition. Triangular arrays are used at 4 points and L-shaped arrays are used at 58 points. L-shape arrays were deployed along road crossings. The triangular arrays consist of 10 receivers and the L-shaped arrays consist of 11 receivers. All receivers are connected to the seismograph through a spread cable. The size of array is 40 to 80m. Figure 3 shows the receiver arrays used in the passive surface wave method. Sampling time is 2msec and data length is about 10 minutes. It takes about one hour for the data acquisition for one point.

In the phase velocity analysis, SPAC (Spatial Autocorrelation) method (Okada, 2003) is employed. Okada (2003) shows Spatial Autocorrelation function $\rho(\omega, r)$ is expressed by Bessel function.

$$\rho(\omega, r) = J_0(\omega r / c(\omega)) \quad (1)$$

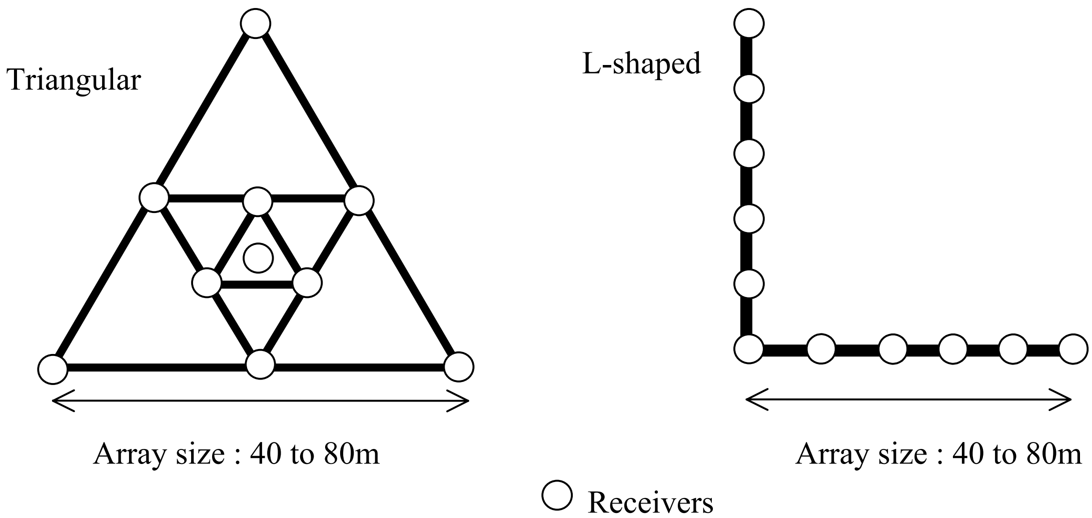


**Figure 3.**: Receiver arrays used in the passive method.

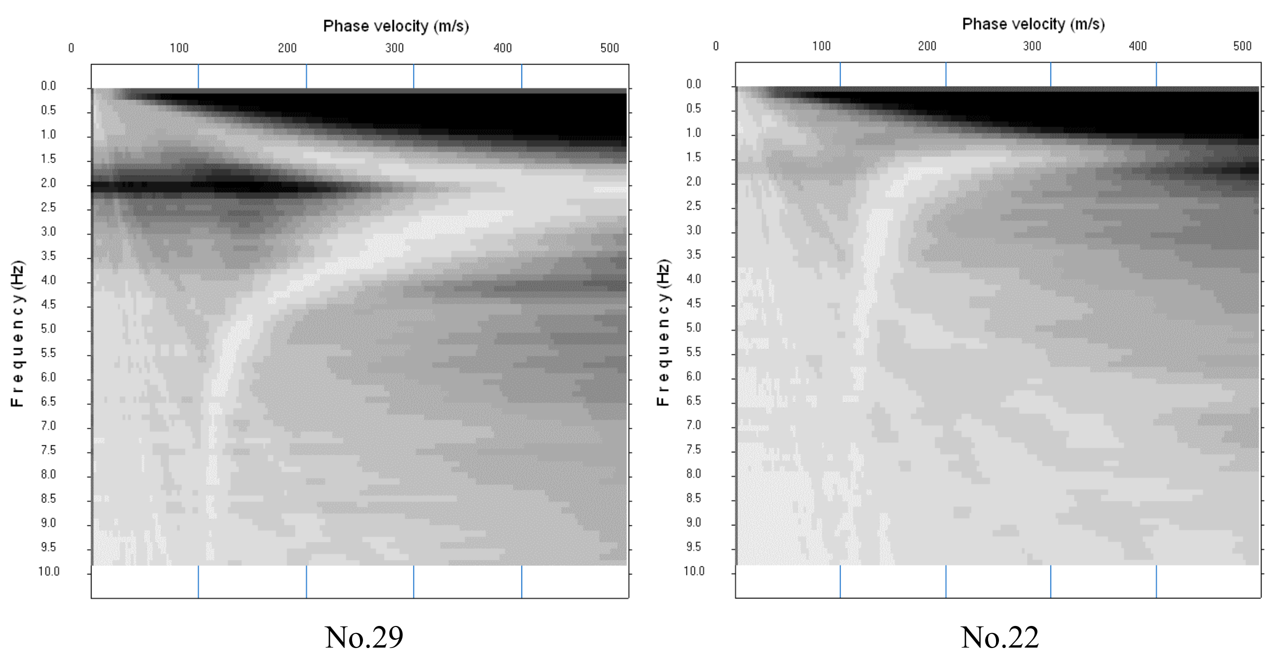


**Figure 4.**: Example of image of phase velocity versus frequency.

Where, $r$ is the distance between receivers, $\omega$ is the frequency, $c(\omega)$ is phase velocity of micro-tremors, $J_0$ is the first kind of Bessel function. The phase velocity can be obtained at each frequency using equation (1). In this survey, phase velocity curves were calculated in the frequency range between 2 and 10 Hz. Figure 4 shows the image of phase velocity versus frequency. The residual between the Spatial Autocorrelation function and the Bessel function is plotted in the figure. We can see that the fundamental mode of phase velocity curve is clearly obtained. Phase velocity curves can be obtained clearly in all observation points as shown in Figure 4. A one-dimensional inversion using a non-linear least square method has been applied to the phase velocity curves and one-dimensional S-wave velocity structures down to the depth of 100m were obtained. . In the inversion, we used the following relationship between P-wave velocity and S-wave velocity (Kitsunezaki et. al., 1990):

$$Vp = 1.29 + 1.11Vs \quad (2)$$

where, $Vs$ is S-velocity (km/s), $Vp$ is P-wave velocity (km/s). In order to assume density from S-wave velocity, we refer to the relationship of Ludwig et al. (1970):

$$\rho = 1.2475 + 0.399Vp - 0.026Vp^2 \quad (3)$$

where, $\rho$ is density (g/cm$^3$). The resultant one-dimensional structures were interpolated into a three-dimensional structure.

## Survey Results

Figure 5 shows the typical phase velocity curves on buried terrace and in buried channel. It is obvious that the phase velocity curves on terrace and in channel have large difference. It implies that the S-wave velocity structures have also large difference between terrace and channel. Figure 6

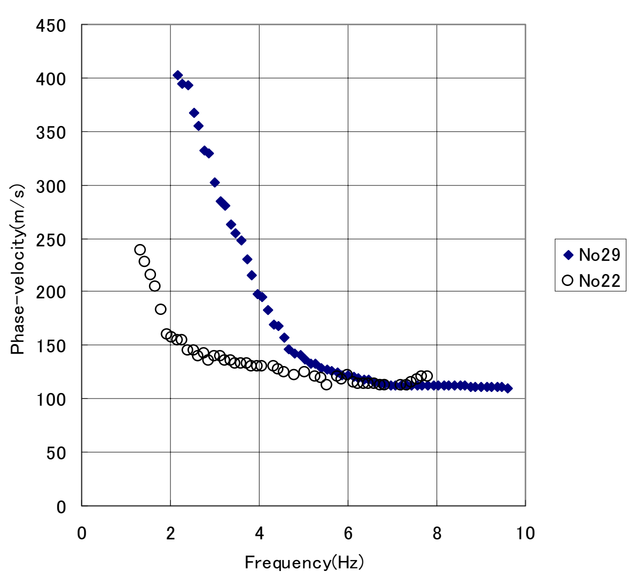


**Figure 5.**: Phase velocity curves on terrace (No.29) and in channel (no.22).

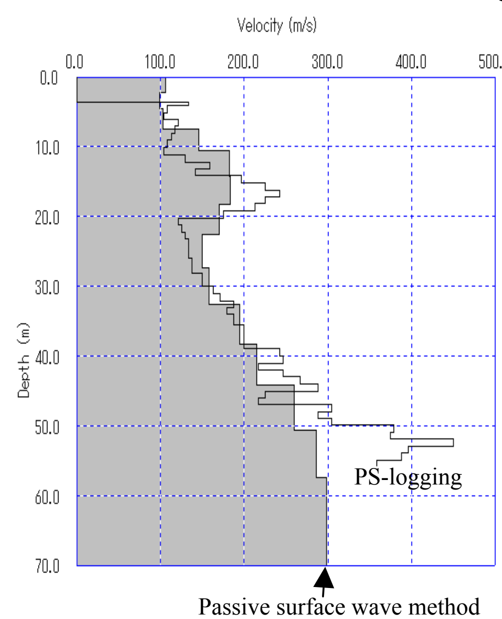


**Figure 6.**: Phase velocity curves on terrace (No.29) and in channel (no.22).

shows the comparison of suspension PS-logging and the passive wave method around the borehole. Although a high velocity layer placed in the depth between 15 and 20m is not clear, the velocity structure obtained through the passive surface wave method agrees with PS-logging very well.
The bottom of alluvial layer is defined at the depth of 50m in the borehole shown in Figure 6. S-wave velocity from the passive surface wave method at the depth of 50m is about 250m/s. Therefore, we assumed the S-wave velocity of 250m/s is the boundary of alluvium and diluvium. Figure 7 shows the depth of the S-wave velocity of 250m/s in the three dimensional S-wave velocity model obtained through the passive surface wave method. The map shown in Figure 7 can be considered as the depth of alluvium bottom obtained through the survey. We can say that the bottom of alluvium obtained through the survey (Figure 7) agrees with that of borehole data (Figure 1) very well. From the Figure 7, it seems reasonable suppose that the boundary of terrace and channel in south side of the Soka Park is straight. The slope of boundary in east and north side of the park is relatively smooth compare with the boundary in south-east side of the park.

## Conclusions

We have carried out the passive surface wave method at 62 points in the 3km square test site in a suburb of Tokyo. The resultant three-dimensional velocity structure clearly shows the shape of buried channels and agrees with the existing borehole data very well. Considering that the demand for the investigation of local site effect is increasing, the passive surface wave method presented here can play important role much more in such situation.

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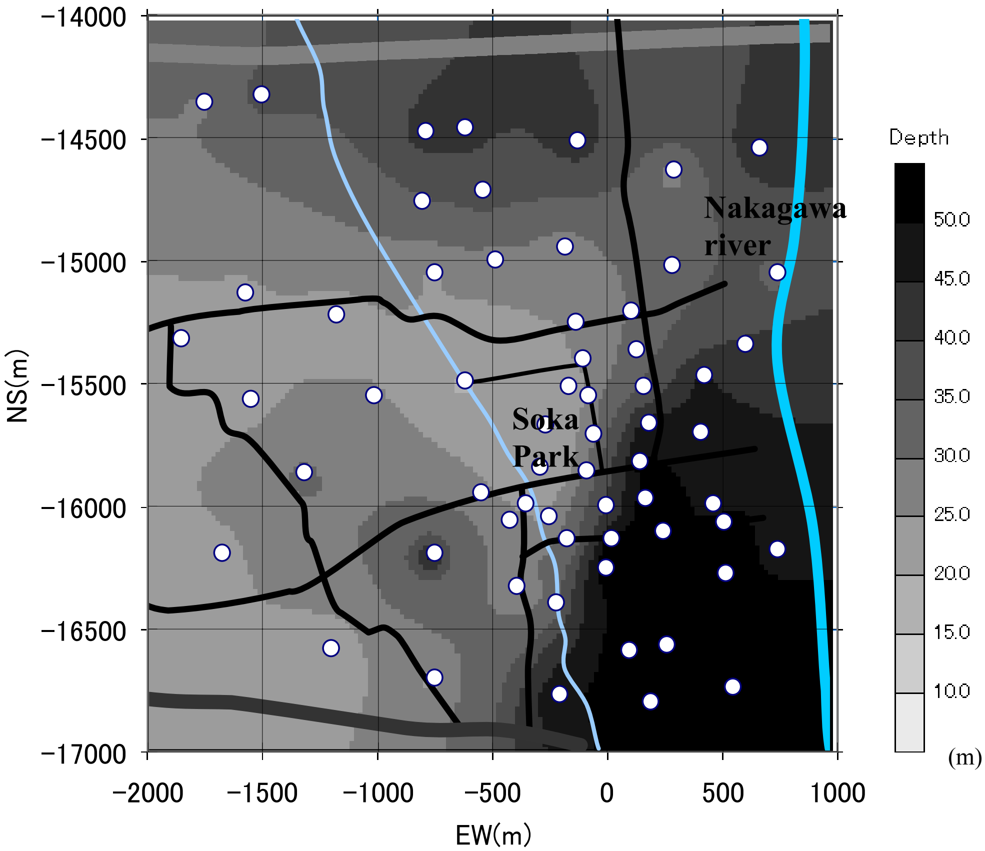


**Figure 7.**: Depth of alluvium bottom obtained through the survey.