Surface wave surveys in the area damaged by ground liquefaction
- A case study in the Kanto region, Japan –
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Summary
A surface wave survey was carried out in Katori city, Chiba, Japan which suffered the liquefaction damage accompanying The Great Eastern Japan Earthquake generated on March 11, 2011, and two-dimensional S wave velocity distribution was obtained. It is known that there is a strong correlation between S-wave velocity and ground stiffness. Therefore, we can know the distribution of the unconsolidated layer at shallow portion by knowing S-wave velocity distribution. As a result, we can understand the shallow portion of the subsurface structure. In the portion, we can interpret structures relating to liquefaction like distribution of the old channel filled with sandy deposit and the shape of the alluvium basement. In the present study, by using S wave velocity distribution, the shallow-portion of the investigation area was classified into some groups such as surface and sand zones and silt layer zones and others. It is impossible to grasp all the details of liquefiable soils only by surface wave surveys. By adding the information on the resistivity distribution and groundwater level distribution which are obtained from the results of the electric surveys and small-scale drilling which are due to be carried out in this area, it becomes possible to interpret liquefiable-soil distribution.

Introduction
The Great Eastern Japan Earthquake generated on March 11, 2011 did serious damage to people's lives and their livelihoods not only by the direct damage of its vibration but also the tsunami, land subsidence, and the liquefaction which follow the earthquake. Moreover, we are anxious about contaminations such as soil pollution caused by the radasative materials scattered by the disaster of Fukushima No. 1 nuclear power plant, salt mixing to the soil and groundwater resulting from a tsunami deposit, and contamination by arsenic, a heavy metal, or other toxic materials. Therefore, the National Institute of Advanced Industrial Science and Technology (AIST) starts a combined geological risk assessment project, and evaluates the risk concerning a liquefaction, an induced earthquake, tsunami, soil pollution, and groundwater contamination (AIST, 2012). This research is a part of liquefaction risk investigation of the project.

In this research, we discuss the surface wave survey result carried out in Katori city, Chiba which suffered liquefaction damage in case of The Great Eastern Japan Earthquake.

S wave velocity is the physical property directly related to the modulus of rigidity and is used as the measure of the stiffness of substances. It is the well-known fact that S wave velocity has good correlation with N value which is frequently used in the civil-engineering field. It is important to obtain S wave velocity distribution in cases where the investigation of the liquefaction which has a close relation with the stiffness of the foundation. In order to obtain the S wave velocity in the shallow subsurface, PS logging using a drill hole is usually carried out. However, the result obtained by the investigation is only data at a certain point. To obtain two- or three-dimensional S wave velocity distribution, many drill holes are required, thereby cost increases. In this research, we carried out the surface wave survey using a land streamer system (Inazaki, 1992), and acquired the S wave structure of the wide area in short period of time.

Survey area and data acquisition
The survey area is the northern coast of the Tone River in the north portion of Katori city, Chiba, Japan. It is the land where the inland sea was filled up with the river sand at the time of the Tone River rerouting of the Edo period. Then, the land was reclaimed further, and it has been used mainly as a paddy field for about 300 years. Many canals and the branches of the Tone River existed there till the early stages of Showa Era.

A surface wave survey was carried out along a survey line of about 3.5 km long in the direction of SSW-to-NNE (Figure 1). In the ordinary surface wave survey, we pierce the earth with the spikes of geophones and make geophones and the ground unify, and use them as receivers. Unlike it, in this paper, we use a land streamer system (Inazaki, 1992) as a receiver system. As compared with the case of the geophone system with a spike, deployment and movement are much easier for the land streamer system, and it can greatly reduce the data acquisition time. Considering low frequency content is dominant in the surface wave signals, we chose the land streamer with geophones of center frequency of 4.5 Hz. A P-wave source so called digi-pulse was used as an energy source. The digi-pulse source is an equipment which generates pulsive P-wave by striking a weight against the plate put on the ground with the elastic
energy of a rubber band. The system used for data acquisition is shown in Figure 2. The main specifications of data acquisition are receiver interval: 1.0m, source interval: 2.0m, source receiver offset: 48-96m, simultaneous data acquisition channel number: 96ch, record length: 4000ms, and sampling rate: 1.0ms. The data acquisition along the survey line of about 3.5 km has been carried out in seven days.

Data processing and analysis

The surface wave survey data were processed using the distributed curve by one-dimensional inversion (Hayashi et al., 2001) by assuming one-dimensional (horizontally layered) structure. Nonlinear least-squares method was used for inversion. In the data analysis processes, S-wave velocity models of 10-15-layer structure were used and the layer thicknesses of the models were fixed. By fixing layer thicknesses, only the S wave velocity of each layer remains unknown, and, as a result, we can stabilize the inversion. Distributions of P-wave velocity and density were determined by the existing materials (SEGJ, 1990; Inazaki et al., 1990) or empirical equations from S wave velocity information. Finally, an S-wave velocity section was obtained by connecting a series of one-dimensional inversion results. The flow of data processing is as follows.

1. Cross correlation calculation of trace in common-mid-point gathers.
2. Conversion to frequency-phase velocity domain, and creation of dispersion curve.
3. Creation of initial model using apparent S-wave velocity structure.
4. Update of S-wave velocity model by inversion.
5. Creation of two-dimensional S-wave velocity structure.

Survey results

The S-wave velocity structure of a surface wave survey result is shown in Figure 3. Figure 3 delineates that the layer at the shallow portion is increasing its thickness from about 8 m to 20 m along with the SSW-to-NNE survey line.

If we see the figure in greater detail, at about 1000 to 1400 m and about 2500 to 3600 m in distance, the extremely low velocity layer with S-wave velocity of 100 m/s or less can be observed at the depth of about 5 m. Judging from boring results carried out in the vicinity of the survey line, this extremely low velocity layer can be interpreted as a silt layer. In addition, at about 300 to 1000 m and about 2800 to 3500 m in distance, we can recognize that the layer with S-wave velocity of about 200 m/s has accumulated on the extremely low velocity layer. Judging from the surrounding drilling results, the layer can be interpreted as a surface layer or a sand layer.
Surface wave survey at a ground liquefaction occurrence area

Conclusions

We discussed in this paper about the surface wave survey in Katori City, Chiba which suffered liquefaction damage in case of The Great Eastern Japan Earthquake. Since we used the efficient land-streamer system for data acquisition, the data acquisition along the survey line of about 3.5 km has been carried out in seven days. We analyzed the obtained data by one-dimensional analysis by assuming one-dimensional (horizontally layered) structure. Nonlinear least-squares method was used for inversion. The shallow-portion geology of the study area can be classified into a surface layer and a sand layer, and a silt layer from S wave velocity distribution of the inversion result.

It is impossible to grasp all the details of liquefiable soils only by surface wave surveys. By adding the information on the resistivity distribution and groundwater level distribution which are obtained from the results of the electric surveys and small-scale drilling which are due to be carried out in this area, it becomes possible to interpret liquefiable-soil distribution.

Figure 3: S wave velocity distribution on the Katori, Chiba survey line obtained by the surface wave. Thickness of the low velocity zone increases from about 8m to 20m along the survey line from SSW to NNE.