Delineation of S-wave velocity structure of pavements and embankments by means of high-frequency surface wave measurements

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Special attention should be paid not only to the surface pavement but also to such artificial layers as embankments and fills when applying near surface geophysics (NSG) to the subsurface up to 30 m depth. Conventional geophysical studies of the Earth’s interior have ignored or treated the near surface as a nuisance or a noise source. Conversely, our social activities have fundamentally been being operated in the near surfaces. Since NSG should play an important role for assessing the present state and future deterioration potential of infrastructures mainly founded on and in the near surfaces, through delineating their heterogeneous structures, and through characterizing their physical properties such as bearing strength and seismic resistance. On the other hand, surface pavement layer, which is a quite common substance in urban areas, has made it difficult to apply seismic refraction surveying because of the velocity overturning, and the existence of a number of buried metallic pipes at shallow depths too for applying EM measurements. In contrast, seismic reflection and surface wave method have the capability of delineating velocity structures in the near surfaces even through the surface pavements. Actually we have conducted a number of near surface surveys in urban areas utilizing SH-wave type and surface wave type Land Streamers. Target depths of the surveys were from 100 m to 5m. We could expand the opportunity of applying NSG to pavement structure surveying when we make the target depth shallower than 1.5 m. One of the most useful tools for ultra-shallow surveys is GPR (Ground Penetrating Radar), and actually it has been widely used for detecting voids beneath the pavement. It can locate voids, however, but does not provide information on physical properties of pavements indispensable for road maintenance. In contrast, surface wave method can yield S-wave velocity structure of the subsurface. Our recent studies have revealed that high-frequency dispersion curves up to 500 Hz were obtained by means of the Land Streamer, developed by the first author, which mounted a conventional 4.5 Hz geophone on a metallic baseplate coupled non-adhesively with pavement surface. In addition, we demonstrated that an accelerometer array tool had wide frequency range up to 4 kHz, but adhesion of accelerometer sensors, it forced time-consuming and dangerous works on roadways, were critical for obtaining high quality records. Dispersion curves up to 4 kHz enabled us to reconstruct S-wave velocity structures at depths of 15 cm to 2 m or more. It was required to obtain dispersion curves up to 8 kHz for the estimation of S-wave velocity and thickness of the uppermost asphalt concrete layer, which was the key for assessing traveling performance of roadway. Then we newly developed a non-contact surface wave measurement tool using an air-coupled microphone array for the structural investigation of pavements. The tool comprises two microphone arrays, suspended 2 cm above the pavement surface. The microphone array observes leaky surface waves under air-coupled condition. Field measurements demonstrated that the tool could measure surface waves which showed clear dispersion in the frequency range from 40 to 8,000 Hz. S-wave velocity structure of the pavement up to 1 m was successfully reconstructed from the higher modes or Lamb mode of surface waves. To certify whether the dispersion curves measured by the tool were valid, we conducted check drilling and forward modelling based on the drilling data. Observed dispersion curves were well matched with those calculated from the actual pavement structure.

Keywords: surface wave, leaky surface wave, high frequency, higher mode, artificial layer

Development of a method to estimate one-dimensional distribution of dielectric constant using electromagnetic waves

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It is important to monitor water distribution under the ground near repository sites of radioactive waste. Water content in the ground and rocks can be evaluated via electromagnetic wave analysis.
Electromagnetic wave analysis has advantages to evaluate water content for the following reasons: (1) The existence of pore water provides significant change in dielectric constant. (2) There is a relation between dielectric constant and degree of saturation. However, it is difficult to evaluate the distribution of dielectric constant in wave propagation direction by existing methods which are based on information of arrival time and amplitude of electromagnetic waves reflected from gap of dielectric constant.
This study presents a method to estimate the distribution of dielectric constant via electromagnetic wave analysis. The proposed method consists of an unscented Kalman filter and a finite element method. The unscented Kalman filter is a nonlinear Kalman filter which can evaluate state values of a nonlinear system from observation signals with zero-mean Gaussian noise. In the estimation process, the nonlinear Kalman filter requires computation of nonlinear transform. In this study, the computation of a nonlinear transform corresponds to the FEM analysis of reflected electromagnetic waves for arbitrary distribution of dielectric constant.
The validity and performance of our proposed method have been confirmed by numerical and laboratory experiments. In numerical experiments, reflected electromagnetic waves computed by FEM are used as observed signals. The estimated distribution of dielectric constant is in good agreement with the correct distribution. In laboratory experiments, reflected waves measured by a ground penetrating radar (GPR) are used as observed signals. The estimation results are not well fitted with the distributions expected. One of the reasons is that finite element analysis doesn’t consider the effects of wave attenuation, and this problem is a future task of this study.

Keywords: Electromagnetic wave, Distribution of dielectric constant, Unscented Kalman filter

Processing of ground penetrating radar (GPR) data for underground cavity by Convolution neural network

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Title
Processing of ground penetrating radar (GPR) data for underground cavity by Convolution neural network

Background
For many years, GPR (Ground Penetrating Radar) systems have being used to detect cavities underneath the road surface. A system on a vehicle are available to acquire a large amount of data with multi channels, such as 21 channels, faster than about 40 km/h driving. Amount of the data has become larger and larger. The accumulated surveyed road path is supposed to more than 150, 000 km.
Today, the experts take a long time to inspect visually such massive data to identify cavities. It also takes years to become a skilled expert. These years, besides development of the new machine learning design, the Machine Learning and parallel computation technology, such as Deep Learning and GPU frameworks and computer hardware show drastic improvement.
Deep Learning approach is supposed to work with the acquired data directly and automatically. It means that automation of recognition and classification of the types of reflectors with the acquired data directly. In addition, the learning network can be improved with the accumulated training data less computation effort as a transfer leraning. Such feature will fit the analysis of the GPR data for underground cavity survey.
Iso et. al. presented “Processing of ground penetrating radar (GPR) data for underground cavity survey by deep learning”, at the 135th SEGJ Conference in 2016 in Japan. It shows a possibility of the being effective of usage of Deep Learning to distinguish cavities, metal pipes and others for 2D GPR cross-section. However, this previous study, in order to classify the target reflectors, users need to pick the specific reflection anomaly, the top of the shape of hyperbolic curves, manually. The classification result failed in some cases, even though considering amount of training data is limited.

Purpose
The aims of new study are 1) eliminating the manipulation of users to pick the target reflectors and 2) mitigating the errors of cavity classification, with the new Deep Learning network. Besides the limited training data, the problems are supposed to be caused by the limitations of the Learning Network design in the previous study. It uses Deep Neural Network with the hidden three layers as a Deep Learning. This is a simple learning network, and it may not be fit to find out the target objective in the large image region. The new study uses the Convolution Neural Network, CNN, design as a Deep Learning to distinguish and locate cavities and the others. The CNN is one of the feed-forward artificial neural network and widely used for 2D image recognition in the other industries these years. The study bases the real acquired data for training images and evaluate with the other set of real 2D GPR data.

Conclusion / Discussion
The results are compared and discussed with the previous study to the recognition accuracy and efficiency of training effort (CPU time and training images) for initial training and transfer learning.

Keywords: Deep Learning, GPR, Automation, data processing, road inspection, cavity survey

Detailed GPR survey for delineating boulders buried in a roadbed of a highway under construction

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We conducted a detailed GPR survey on a highway under construction to detect and map boulders in a roadbed buried against regulations on embankment materials. Buried boulders in roadbeds should be eliminated because they might cause surface pavement undulation and would deteriorate drivability. A 540 m long, 20 m wide zone was covered within three days by two parties, each composed of two of us, by means of two sets of high-precision GPR tools with the aid of VRS RTK-GNSS positioning systems. Soon after the primary field survey, we quickly processed the acquired data within two days, and extracted a total of 148 anomalies in the zone. We then conducted the secondary survey uninterruptedly to precisely locate the points where anomalies were identified. The located points were immediately dug with a backhoe to certify whether boulders had been buried or not. It took only one and half day for the secondary field survey. As a result, boulders of 20 cm to 100 cm in size were actually excavated from 146 points of the located 148 anomaly points. This extremely high hitting ratio was mainly supported by the precise positioning system which enabled us to locate back to the anomaly position within 2 cm. In addition, we made a criterion to discriminate the anomalies generated from buried boulders based on GPR diffraction patterns. The criterion was quite helpful to identify anomalies from buried boulders not from other objects such as metal fragments. Owing to the high performance GPR survey within a total of 6.5 days from the primary survey to the excavation of identified boulders, we successfully contributed to minimize the delay in embankment works of the highway under construction.

Keywords: Highway geophysics, GPR, roadbed, boulder

Evaluation of groundwater in fractures adjacent to tunnel using information of waveforms of Ground Penetrating Radar

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For construction of underground structures in a rock, it is important to characterize the ground water flow in the fracture. Fractures developing around the tunnel during the excavation, which is called as EDZ (Excavation Damaged Zone), result in issues related not only to the mechanical stability of the rock cavern, but also to the groundwater flow paths. Specifically, in terms of the safety assessment of geological disposal of radioactive waste, the groundwater management of rock caverns for oil/LPG storage using hydraulic containment system, or planning of countermeasures for water seepage of tunnels, it is important to have a thorough understanding of the groundwater conditions around the tunnel.

As the GPR (Ground Penetrating Radar) method is unique technique to survey the groundwater condition, indirectly, and with no disturbance of original ground water condition, so the GPR is possible to grasp the water condition in the fractures around the tunnel, however, the output is just the profile image of the fractures so far. In this study, the change of reflected waveforms (amplitude or frequency) of GPR is focused in order to estimate the water content and concentration of liquid in the fractures, and the target of this study is to show the possibility of application of the information of GPR waveforms to evaluate the groundwater in the fractures.

Firstly, based on the results of theoretical discussion of electromagnetic wave and numerical simulation using FDTD method, it was concluded that the change of water content, saturated or non-saturated condition and the existence of high conductivity reflector have influence on the waveforms, that is, the change of amplitude and dominant frequency of reflected wave. So, the change of amplitude and frequency would be a possible indicator to evaluate the water condition in the fractures.

Next, in order to validate the possibility of application of GPR in the actual site, three types of experimental study were conducted; (1) preliminary test using the artificial fractures, which consisted of the wooden cement-boards between a concrete block (Masumoto and Kurihara, 2014), (2) verification test on the surface of the concrete placed on the granitic rock with fractures to evaluate groundwater permeation in the rock of lining backfaces (Masumoto and Kurihara, 2015), (3) verification test along the side wall of 500m access tunnel of Mizunami Underground Research Laboratory of JAEA to estimate the fractures around the tunnel as flow paths (Masumoto and Takeuchi, 2016).

From these results of monitoring of the reflected waveforms from the target fractures using GPR, it could be concluded that the difference of water condition in the fractures caused the change of intense of amplitude and spectrum due to the results of spectrum analysis of reflected waveforms. The results indicated that the water condition in the fractures and the flow paths or transport channels along the fractures could be evaluated using the information of reflected waveforms of GPR.

In the future, this non-destructive method using GPR could be applied to monitor the submerge process of unsaturated zones around rock caverns, to measure the break-through process in tracer tests 2-dimensionally, and to monitor the permeation of grouting materials in grouting work.

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Keywords: Ground Penetrating Radar, Excavation Damaged Zone, Groundwater

Resistivity monitoring of water-leaking paddy field filled with water

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A large earthquake causes high hydraulic conductivity zones in the soil and the high hydraulic conductivity zones of soil often lead to leakage of water from a paddy field. Although the locations of infiltration have to be estimated, the locations cannot be observed from the surface. Electrical resistivity survey can provide spatial geological information non-invasively because electrical resistivity is strongly affected by the level of water saturation in the soil. After the 2016 Kumamoto earthquake occurred, although the amount of leakage from a paddy field increased, the location of infiltration was not observed. In this study, resistivity monitoring of a water-leaking paddy field filled with water was conducted. A resistivity change derived from 2D inversion of resistivity survey data was small beneath the paddy field and the resistivity beneath the bank of the paddy decreased 4 hr. after the start of filling with water. Since some rain occurred before the filling test, there was a possibility that the high saturation level caused no change beneath the paddy field. However, the resistivity beneath the paddy flied decrease 24 hr. after the start of filling with water.
These results suggest that the leakage occurred beneath the bank of the paddy rather than beneath the paddy field.

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Keywords: Resistivity monitoring, water-leaking paddy field, earthquake

Imaging of the internal geophysical structure by means of near surface geophysical surveys at a road embankment failure site.

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A road embankment which is about 8 m high was partly collapsed by a heavy rainfall. This embankment had been experienced a strong shaking two months before the collapsing caused by the 2016 Kumamoto earthquake. Surface cracks and deformation were identified on the body just after the earthquake. We conducted near surface geophysical survey to clarify a collapse process and internal geophysical structure of survived part of the road body. Our survey consisted of GPR and DC resistivity tomography. We used Utility scan DF system synchronized with GNSS antenna for a GPR survey. This system can obtain high accuracy positioning data within +/- 1 cm under RTK-FIX condition. In DC resistivity survey, current and potential electrodes were set alternately at 50 cm intervals along a line which cross at a collapsed part. As a result, GPR profile imaged a dipping structure behind the collapsed part. Resistivity structure showed relatively high resistivity as the embankment and imaged frontal thrust clearly. A possible sliding surface was interpreted on the basis of resistivity structure and surface displacement trajectory between before and after collapse of 5 points. In conclusion, GPR and DC resistivity tomography was helpful to delineate internal deformation structure and interpret a possible sliding surface. The survey result demonstrated the effectivity of detailed near surface geophysical surveys.

Keywords: Embankment failure, Near surface geophysics

Geoelectrical monitoring of changes in water content in an embankment using a large-scale rainfall simulator

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Measuring the temporal variation of water content in a slope is important for preventing slope disasters. We conducted repeated monthly geoelectrical surveys since February 2011 on one slope of an embankment in the large-scale rainfall simulator of the National Research Institute for Earth Science and Disaster Resilience (NIED). A survey line, which is 18m in length, was set up across the slope. Thirty-seven electrodes were arranged permanently at 0.5-m intervals along the line. Measurements of near-surface soil water content and temperature have been conducted at five places along the line. The embankment is usually outdoors and observations in natural weather have been performed. The results of the repeated geoelectrical surveys show that short-term changes in resistivity correspond to changes in water content caused by rainfall.
In order to confirm the changes in resistivity and water content by rainfall in detail, we conducted the artificial rain experiments, controlling the total amount and intensity of rainfall using the mobile simulator. Eleven experiments were conducted in 2012, 2013, 2014. It was difficult to obtain the rapid change of resistivity structure due to the heavy artificial rain with ordinary geoelectrical equipment, because the analysis of resistivity structure requires measurement by much electrode array combination. In these experiments, therefore, we performed only a continuous measurement using a Wenner array with "a" spacing of 0.5 m and 1 m. The apparent resistivities changed significantly with a rapid change in water content, indicating that geoelectrical monitoring is effective in assessing the condition of a slope during rainfall.
In three experiments in 2015, we used a high-speed resistivity profiling system which can provide 576 (24x24) data in about 10 seconds for the resistivity monitoring. The pole-pole resistivity data were collected at intervals of 1 or 2 minutes and a series of resistivity sections were obtained along the slope of the embankment. The result shows that the high-speed geoelectrical monitoring is effective for observing soil moisture changes caused by heavy rain in real time.

Keywords: Geoelectrical monitoring, resistivity, water content, large-scale rainfall simulator, slope disaster

Case studies of the survey of induction method using GEM-2 -- along the sand beach and above the intrusive rock --

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GEM-2 is the electromagnetic instrument used in this study. Since it can simultaneously operate multiple frequencies in the broadband domain from 300 Hz to 96 kHz, we will be able to estimate the distribution of the conductivity to the depth direction. The purposes in this study are detection of the boundary of freshwater of the creek and seawater at Katsurahama coast in Akita city and examination on the anomaly of the electrical conductivity above the intrusive rock at the quarry site in Sugisawa, Daisen city, Akita prefecture.
On the exploration at Katsurahama coast, the freshwater of the creek has the characteristics of the low electrical conductivity of 0 to 40 mS/m. On the other hand, the high electrical conductivity is seen on a part of the western sea side. The change in the low conductivity to the depth beneath the creek cannot be observed, but on the part of the high conductivity on the sea side the change to the depth can be detected. The conductivity is higher at the shallower depth compared with deeper place at the part of the high conductive western sea side. I consider that the high electrical conductivity of the shallow sea side is more influenced by the invasion of the seawater.
At the quarry site in Sugisawa, the anomaly of the low electrical conductivity surrounded by the high conductivity is seen above the intrusive rock by the exploration. The distribution of the high electrical conductivity is considered to be due to alternation and mineralization in the contact part of intrusive rock and pre-existed rock. Examining the tendency of the depth change of the distribution of the low conductivity surrounded by the high conductivity above the intrusive rock, it is said that the structure change cannot be seen to the depth from 5 to 19 m.
I understand that the resolution by the exploration using GEM-2 is excellent at shallow depth, but that GEM-2 is easy to catch the noise when the exploration depth exceeds 10 m. In other words, GEM-2 is easy to catch the noise when we operate it with low frequencies. It is sometimes necessary to remove noises on low frequency operation. In this study, I successfully remove the noises and improve the data with taking the median values and using the running mean method on a finite length of data section.

Keywords: electromagnetic survey, induction method, GEM-2, freshwater/seawater interface

Changes in phase velocity of Rayleigh waves at the Hinode area, Itako, Ibaraki, Japan, due to the construction by the ground water lowering method: A case study of the miniature array analysis of microtremors

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The Hinode area, Itako, Ibaraki, Japan suffered devastating disasters of liquefaction by the 2011 off the Pacific coast of Tohoku Earthquake. The Itako City has been conducting the construction method called the ground water lowering method to avoid the second devastating liquefaction by some huge earthquakes in the future. We report the changes in phase velocity of the Rayleigh waves at the Hinode area between two periods before and after the construction work starting, as a case study of the miniature array analysis of microtremors (Cho et al., 2013).
The construction period of the ground water lowering method was from April 2013 to March 2016. Currently, drain pipes has been buried at the depth of 3m along all paved roads in the Hinode area following that method. The ground water has been pumped up since May 2016. It is evaluated that a large liquefaction will never be met again by lowering the water level to the depth of 3m and keeping it at all times (Itako City, 2016).
We conducted measurements of microtremors using miniature arrays at an interval about 200m along an east-west survey line with the length of 3.2km, which crossed the Hinode area (about 2.8x1.4km) and its surroundings. The microtremor array used there was basically a set of a standard four-point array with a radius of 0.6m and a three-point irregular array with a radius about five meters. The observation duration was about 15min at each point. These microtremor surveys were conducted on August 2012 and on the begging of May 2013. Meanwhile, Yokota et al. (2016) conducted surface wave surveys on December 2012 along three survey lines with lengths from 1.2 to 1.6km, which includes the Hinode area and the northern extensions. In this study, we regard the data from the east-west survey line of microtremors and the two north-south survey lines of surface waves as the "data before the construction work starting".
As the "data after the construction work starting", we conducted measurements of microtremors using miniature arrays along the above three survey lines on September and October 2015. In the field measurements, we took care that each installation point of the microtremor arrays was the same as before. We deployed microtremor arrays at the interval about 100m along the surface wave survey lines. Importantly, all measurements of microtremors were conducted by installing the seismometers on the shoulder of a paved road, so that it is expected that the data after the construction work starting include the direct effects of the construction.
We analyzed the microtremor data along the east-west survey line and compared between the dispersion curves from the data before and after the construction work starting. As the result, it was shown that phase velocities obtained within the Hinode area increased especially in high frequency ranges. On the basis of a simple conversion method from a dispersion curve to an S-wave structure, these changes appeared to correspond to the increase in the S-wave velocities to the depths shallower than several meters. Similar features can be seen in the S-wave structures obtained by the microtremor method along the two survey lines of surface waves. This means that the general pattern of the distribution of the S-wave velocity obtained by the microtremor method is very similar to that obtained by the surface wave method with the exception of one point: the S-wave velocities to the depths shallower than several meters in the Hinode area by the microtremor method was particularly high (Fig. 1).

In this way, we observed changes in S-wave velocity only in the shallow portions in the Hinode area. This is qualitatively natural and may show the potential of the miniature array analysis of microtremors. We will make detailed examinations on the limitation and possibility of the miniature arrays in more qualitative manner.

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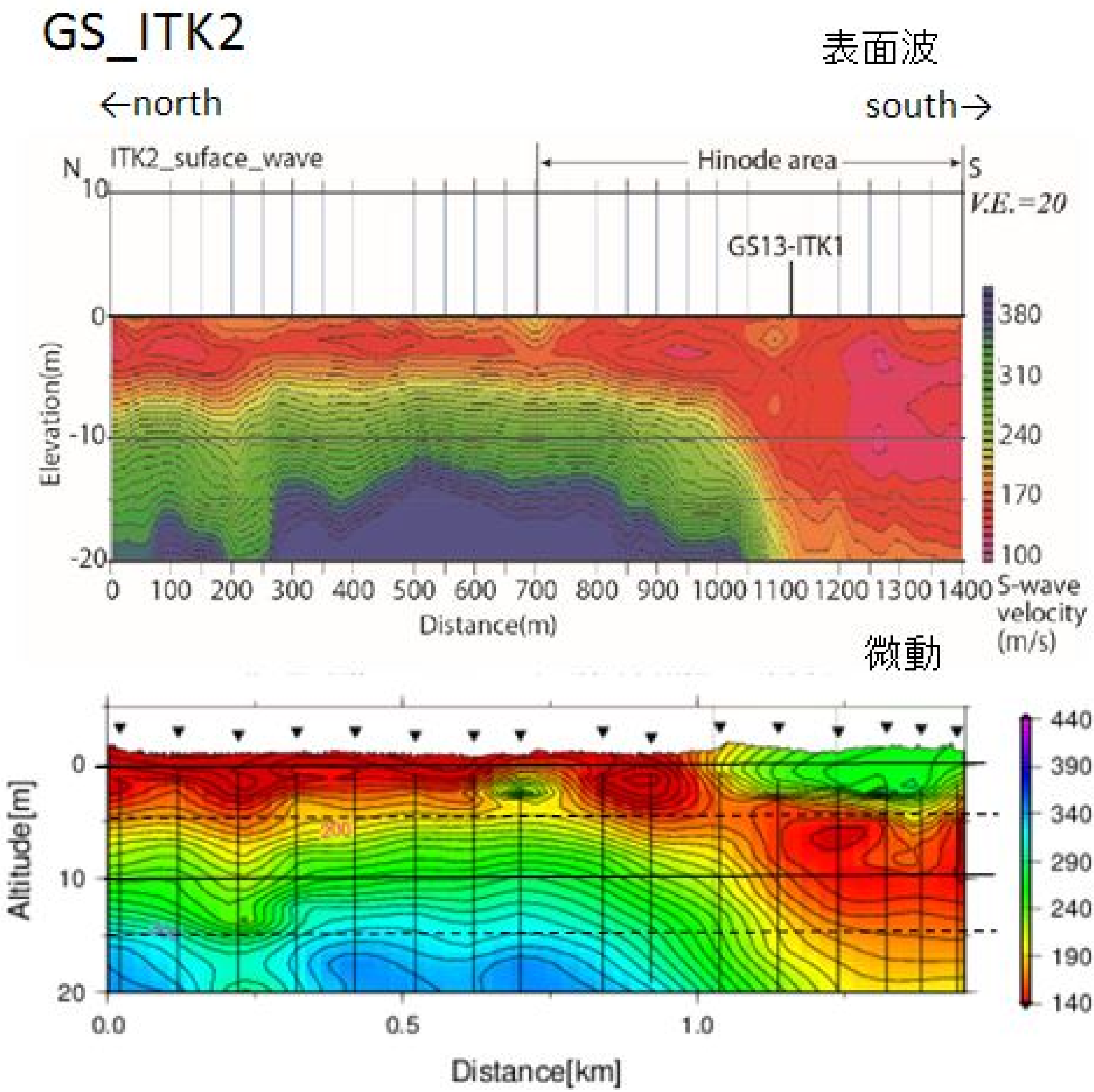
Keywords: microtremor, array, surface wave, liquefaction, the 2011 off the Pacific coast of Tohoku Earthquake, the ground water lowering method



Distrubution of saline-freshwater in shallow groundwater in the lower reaches of Nabaki River, the Kujukuri Plain, Chiba Prefecture, Japan

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Kujukuri Plain, Chiba Prefecture is a coastal area, which is of low topography and also one of the places in where land subsidence is reported to have been occurring for over 40 years. Nabaki River is a tidal river located in the sourth of the Kujukuri Plain and the seawater flowing into the river from the mouth at high tide time is reported. Therefore, the distribution of salt and fresh groundwater and possible influence of the tidal river to the surrounding groundwater is required to understand. In this study, we discuss to reveal the distribution of salt-fresh groundwater and a process of groudwater salinization by the method of resistivity survey and water chemistry. The overall tendency is that the shallower part of the subsurface (about 3 to 5 m) has a higher resistivity value and the deeper part (deeper than about 5 to 7 m) has a low value. It is interpreted that freshwater exists in the subsurface shallower part and groundwater with high salt concentration is distributed in the deeper part. On the other hand, in some areas, the groundwater with high salt concentration (low resistivity zone) indicated a distribution that sloped from shallow to deep with the distance from the Nabaki River, and the effect of the tidal river is suggested as one of the factors.

Keywords: Nabaki River, Resistivity survey, saline-freshwater, shallow groundwater

Characterization of the aquifer at Tottori sand dunes using NMR and GPR sounding

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We have conducted the surface NMR and GPR surveys at Arid Land Research Center, Tottori University. The surface NMR is a non-destructive survey for characterizing aquifer using loop on the ground surface which are used for transmitting and receiving coil. The NMR signal is proportional to the magnitude of the magnetic field, so the signal obtained by the surface NMR is much smaller than other NMR method such as NMR logging, because the magnetic moment of the earth is very weak. Therefore, the surface NMR is mostly difficult to apply in the suburb of an urban area. The research center is located at only a few kilometers away from the Tottori city and the EM noise level is not so small. Yet, the noise level is within the acceptable levels by noise tester. A 35 meter side eight-square loop is adopted in our survey, and total 12 pulse moments are used to obtain a full sounding curve. Only less noise data are acquired and more than 250 data are stacked to increase the signal to noise ratio. A typical NMR signal showing exponential decay curve was observed at a certain pulse moment. Full sounding result is compared with the forward modeling and we inferred that a few meters thin aquifer exist at 30 meter depth.
GPR is usually applied for shallow subsurface investigation down to a few meters deep. Especially, the penetration depth will be shallower for the heterogeneous subsurface or clayey soils. However, the penetration depth goes deeper for the homogeneous thick sand deposit such as Tottori sand dunes. We completed the profile and the CMP surveys by 35 MHz antenna. The velocity of the EM wave is calculated from the CMP measurement and we created the depth profile using the calculated EM velocity. A clear reflection boundary is observed at around 29 to 30 m depth in the depth profile. The depth of the reflection agrees with the actual water level measured at several monitoring wells in the survey area.
The surface NMR enables us to obtain one dimensional result of water table and thickness of the aquifer, while GPR provides two dimensional image of water table. Therefore, combining the two methods must be an effective method to characterize aquifer in arid area.

Keywords: Surface NMR, GPR, groundwater, Sand dune

