Japan Geoscience Union Meeting 2014
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SSS35-P01 Room:Poster Time:May 2 16:15-17:30

Sophistication of microtremor methods to survey shallow structures, PartI: Development of automatic reading algorithms

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We have been seeking an efficient way to maximize the potential of the microtremor methods for shallow surveys. It is considered that a practical approach has been gained in the observation by the development of portable seismometers (Senna, 2006, 2012) and by the finding of the full usability of the data obtained by a miniature array (radius $<$1 m), optionally together with a small irregular-shaped array (radius less than 10 m) consisting of three seismometers (Cho et al., 2013a).

As an efficient way to infer an S-wave velocity structure, we consider that a classical, simple profiling method (SPM), where a dispersion curve is directly converted into an S-wave velocity structure (e.g., Heukelom and Foster, 1960), is a good scheme from a view point of simplicity, thus, the balance between the efforts and the information to be extracted. It is true, however, that we frequently like to increase to resolution. Facing this dilemma, we suggested a simple tool "H/V depth conversion" (Cho et al., 2013). We found that the use of an H/V depth conversion followed by a simplified inversion method (SIM) of Pelekis and Athanasopoulos (2011) can in fact increase the resolutions (e.g., Senna et al., 2013; Yoshida et al., 2013).

The current problem is to further promote the efficiency in the data processing procedure. A visual reading of analysis results, which we take at the current time, is time consuming to deal with a vast mount of microtremor data, now obtainable by a streamlined observational procedure. The reproducibility and biases constitute other kinds of problem of visual reading.

To address this problem, we invented the following automatic-reading algorithms. We applied them to observed data consisting of multiple arrays along a measurement line. As the results, natural images of two-dimensional S-wave velocity sections were obtained, not considerably different from the one obtained by visual readings (Senna et al., 2014).

Automatic readings of phase velocities

Let us suppose that multiple dispersion curves have been obtained by either multiple arrays or multiple analysis methods (i.e., nc-CCA, CCA, and SPAC methods) at a single observation point. In the first step, apply the following procedure to each dispersion curve. (i) Divide the frequency range used for analyses into equally-spaced intervals (bins) in a logarithmic scale. Take an average of phase-velocity data in each bin. (ii) Exclude the results from the analyses either when the wavelengths relative to an array radius lie out of the range defined a-priori for each method or when they exceeds the analysis limits having been evaluated by the use of an array with a sensor at the center point. Also, exclude the results when they seem to align in a line passing through the origin.

An automatic reading is obtained for each bin by averaging all values left after the procedure (ii). Readings are deleted, however, when they seem to align in a line passing through the origin.

Automatic readings of peak and troughs of an H/V spectrum

First, an H/V spectrum obtained at a single observation point, or an average spectrum if there are multiple spectra as a representative value, is smoothed using a spectral windows having a frequency-dependent window width. Peaks and troughs of the spectrum are searched from the lower side of the frequency range by using the derivatives. We search pairs of a peak and a trough to stabilize the analysis result: A pair is excluded from the reading results when the difference in either frequency or H/V ratio between a peak and trough is smaller than a threshold. Also, a pair is excluded when a peak (trough) value is smaller than that of an anterior peak (trough). The peak and trough of each pair, thus obtained, are used for the depth conversion, and the resulting depths are averaged to be the representative depth obtained by an automatic reading.

Keywords: Microtremor, velocity structure, surface waves, phase velocity, expolation method, array

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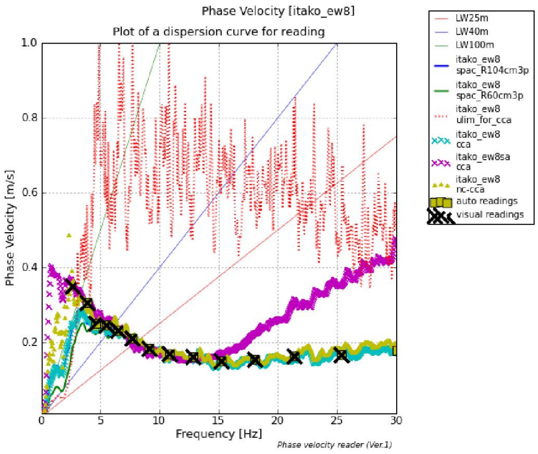

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Sophistication of microtremor methods to survey shallow structures, Part2 : Application of automatic reading algorithms

SENNA, Shigeki[1*] ; CHO, Ikuo[2] ; FUJIWARA, Hiroyuki[1]

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We have been seeking an efficient way to maximize the potential of the microtremor methods for shallow surveys. It is considered that a practical approach has been gained in the observation by the development of portable seismometers (Senna, 2006, 2012) and by the finding of the full usability of the data obtainable by a miniature array (radius less than 1m), optionally together with a small irregular-shaped array (radius less than 10 m) consisting of three seismometers (Cho et al., 2013a).

As an efficient way to infer an S-wave velocity structure, we consider that a classical, simple profiling method (SPM), where a dispersion curve is directly converted into an S-wave velocity structure (e.g., Heukelom and Foster, 1960), is a good scheme from a view point of simplicity, thus, the balance between the efforts and the information to be extracted. It is true, however, that we frequently like to increase to resolution. Facing this dilemma, we suggested a simple tool 'H/V depth conversion' (Cho et al., 2013). We found that the use of an H/V depth conversion followed by a simplified inversion method (SIM) of Pelekis and Athanasopoulos (2011) can in fact increase the resolutions (e.g., Senna et al., 2013; Yoshida et al., 2013).

The current challenge is to further promote the efficiency in the data processing procedure. A visual reading of analysis results, which we take at the current time, is time consuming to deal with a vast mount of microtremor data, now obtainable by a streamlined observational procedure. The reproducibility and biases depending on analyst constitute other kinds of problem of visual reading.

To address this problem, Cho et al. (2014, thismeeting) invented automatic-reading algorithms. In this study we test their algorithm by applying it to observed data to compare the results with those obtained with visual readings. Our method of observation and analysis is described in the following.

1. Observation

Observation duration is set to 15 minutes irrespective of the array shape, where either miniature arrays with a radius of 60 cm or irregular-shaped arrays with radii about 3 to 10 m are used.

2. Automatic analyses and readings of phase velocities and H/V spectra

The selectin of the data portions and the spectral analysis are automatically executed by using the software BIDO. Cho et al. (2014)'s algorithms are used for automatic readings of phase velocities and H/V spectra.

3. Inferring 1D S-wave velocity structures and constructing 2D sections

A dispersion diagram, represented by the relation between the wavelength, L, and phase velocity, Vr, is converted into a 1D S-wave structure having the relation between the depth, D, and S-wave velocity, Vs, where relations Vs= Vr/0.92 and D=0.375L are used (SPM). The resulting 1D structures are spatially interpolated to obtain a 2D section, where H/V depth conversions are overdrawn.

The above procedure from 1 to 3 is fully automatically executed. Incidentally, this study include no examination on SIM because no automatic algorithm has been developed yet because of the robustness problem.

We applied the above procedure to microtermor data obtained along survey lines in four different areas with variable geological environments (e.g., Itako City, Hadano City, Kashiwa City, Urayasu City). As the results, natural views of 2D S-wave velocity sections are obtained in all cases, similar to those obtained by visual readings. Furthermore, resulting velocity sections are consistent with other kinds of subsurface structural data (i.e., geological sections, N-value distributions, the 3D soil model of Senna et al. (2013)). We consider that, needing further improvement, Cho et al. (2014)'s algorithms can provide us with acceptable results at the first stage of automating the analysis procedure.

Keywords: Microtremor, velocity structure, surface waves, phase velocity, array, underground structure model

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Future Initiatives of development of microtremor survey observation system

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The microtremor observation has treated till today as physical investigation information, including the structure model creation for strong motion prediction of the researcher and engineer , etc.

If microtremor observation can observe easily and the observed data can be easily transmitted to a database with information on that observation point, it can expect that the number of collection of observational data will increase explosively in the future because an amateur can also observe, and the advancement of structural model and prediction of seismic strong motions will be attained by leaps and bounds.

It will become an unprecedented thing which leads to grasp of detailed damage distribution, and the improvement in accuracy of real-time earthquake information from the above.

Keywords: microtremor, survey observation system, cloud system, big data

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Estimation of phase velocity of Rayleigh wave using linear array

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Since the spatial autocorrelation (SPAC) method has been proposed by Aki (1957), the observation using a circular array of evenly spaced sensors and a central sensor becomes a commonly used measurement technique in the microtremor survey method (Okada, 2003). However, in practice, the strict arrangement of sensors required by the method is difficult to conduct because of the limit of real environment. In order to slacken the requirement of the arrangement, Chavez-Garcia et al. (2005) discussed the validity of performing the SPAC method with a linear array. However, the conclusion of this research is result-based and is not backed by theoretical demonstration. Aki's autocorrelation coefficient could be alternatively seen as the azimuthal average of CCFs (Okada, 2003; Shiraishi 2006). A CCF consists of the Bessel function and an error term which varies with the azimuth of sources. By taking the azimuthal average, the error term vanishes and direct J_0(kr) can be obtained. The discrete formula of the CCF offers the possibility of extending the original SPAC method. In this research, we develop the solution by controling the error term in CCF which can obtain directly the phase velocity instead of using records of sensors in a line instead of azimuthally arranged ones.

Under the assumption: 1) Only the fundamental mode is dominated. 2) Different sources are not correlated, the real part of discrete formula of CCF could be expressed as (Shiraishi, 2006). If we neglect the terms of order larger than 6, we can obtain:

Re(γ_{pq}=J_0(kr)-2J_2(kr)$\sum\lambda_l$cos2θ_l+2J_4(kr)$\sum\lambda_l$cos4θ_l. It can be seen that there are only three unknown variables kr, $\sum\lambda_l$cos2θ_l and $\sum\lambda_l$cos4θ_l. It is required of at least three sensors (3 different intervals) to solve the 3 unknown variables theoretically. The three sites need to be in a line to make the three CCFs share the same unknowns. Because of the coupling variables and non linear functions, we use the genetic algorithm and particle filter to solve out the optimum solution.

In order to comfirm the validity of this new theory preliminarily, the simple wavefield composed of unidirectional plane wave is used to examine the accuracy of estimating phase velocity obtained from a linear array with 3 sensors. The distances between adjacent sensors (r and 0.5r, r=30m) are set to be different so that we can have totally 3 different CCFs to solve out the optimum solution. Except for the analytical simulation, we also applied a field test to examine the availability of the new method. We have applied field test to comfirm the availability of the method. Observation was conducted on 23 October 2013 at the parking lot of Zoorasia Yokohama Zoological Gardens (ZRS) in Yokohama city of Japan. We deployed 7 seismometers (KVS-300, moving speedometer) constituting two linear arrays. The two linear arrays forms an angle of 60 degree so that the SPAC method could be applied for confirmation.

In the analytical simulation, we confirmed the availability of the new method. The sensitivity of CCF with respect to phase velocity depends on the direction of linear array. When the sensitivity is low, the estimation will be bad. Hence, it is better to use at least two linear arrays forming an angle (90 degree is the best). In the field test in Yokohama, we applied both the SPAC method and the new method using 7 speedometers. Both SPAC method and the new method show good match with the theoretical dispersion curve. The new method shows narrower effective scope and shows some unstablity in both low and high frequency range. Through both simulation and field test, the availability of the new method has been confirmed. This new method makes the arrangement of sensors easier which needs only two linear arrays with a non-strict angle. In the future, we will study more about improving the inversion technique and the application of linear array.

Keywords: SPAC method, linear array, coherence complex function, particle filter

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Estimation of Subsurface Structure using Microtremor Observation in Ogasawara Iwo-To Island

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Ogasawara Iwo-To island is an active volcanic island which is located on the southernmost part of Izu-Ogasawara arc. The microtermor obserbation was carried out during the period from December 18 to 21, 2013 in Ogasawara Iwo-To island. The microtremor measurements were performed at 54 sites as 3-component seismometers for horizontal-to-vertical spectral ratio (HVSR) analysis. The obtained HVSRs of microtremor are used to determine the dominant frequencies of vibration of the subsurface structures beneath several recording sites in Ogasawara Iwo-To island. The H/V peak period varies from 1.1 to 3.5 sec.

For using the SPAC method of microtremor, the circular-array microtremor data were recorded by 6 seismometers distributed along the circumferences of two circles as well as a seismometer deployed in the center at two sites in the center of the island. The phase velocities and the S-wave velocities of the subsurface structures down to a depth of several km were estimated at each site from the microtremor data by using the SPAC method.

Keywords: microtremor, Ogasawara Iwo-To Island, subsurface structure

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Determination of Subsurface Structure of the Mt. Daisen area in Tottori Prefecture by Microtremor and Gravity Survey

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Earthquake damages occurred by the earthquake that occurred at the Middle West of Tottori in 1983 , 2002 and the 2000 Western Tottori earthquake in Mt.Daisen area of Tottori Prefecture. It is supposed that the damage influenced the subsurface structure. It is important that the information of subsurface structures is obtained for prediction of ground motion in the area. Microtremor and gravity surveys were carried out in the plains of the shore part and Mt.Daisen area. S-wave velocity models are obtained at the array observation 3 sites and predominant period distribution at 3-components observation newly. The gravity anomalies were obtained by gravity survey data newly.

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Estimation of inter-station Green's functions using microtremor array data

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The seismic interferometry technique is used to evaluate seismic velocity structure beneath two observation sites [e.g., Ma et al. (2008); Yamanaka et al. (2010); Asano et al. (2012); Hayashida et al. (2014)]. The technique can be applied under the assumptions of non-stationary and uniform distribution of microtremor (ambient noise) sources and it is important to investigate whether the data satisfy the conditions. The array observations of microtremor [Yoshimi et al. (2012)] were conducted at 13 sites in Niigata prefecture, Japan. The surveys were carried out for more than 10 days per site and each array consists of three equilateral triangular arrays whose radii range from several hundred meters to several kilometers. Here we used the data to estimate inter-station Green's functions with the seismic interferometry technique. The stacked cross-correlation functions (CCFs) of microtremor showed coherent and dispersive wave trains in frequency ranges between 0.4 and 1.0 Hz for the small array, 0.2 and 0.7 Hz for the middle array and 0.1 and 0.6 Hz for the large array. The wave trains derived for each array correspond well to each other regardless of azimuth angles, showing the effect from the abnormal microtremor source can be negligible in this study. We also calculated theoretical Green's functions from the estimated S wave velocity structures with the spatial autocorrelation (SPAC) method for each site, assuming 1D velocity structure. The agreements between the calculated Green's functions and the derived CCFs from the seismic interferometry are generally good, especially at lower frequencies. Our results suggest that a combination of velocity structure estimation with surface-wave phase velocity (conventional array methods) and velocity structure validation with Green's function (seismic interferometry technique) provides better estimations for S wave velocity structures.

Acknowledgements:
We used the microtremor array data observed in a research project funded and supported by Japan Nuclear Energy Safety Organization (JNES).

Keywords: microtremor, seismic interferometry, Green's function, group velocity, SPAC method

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Seismic basement structure estimated from seismic interferometry and microtremor analysis

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Recently, seismic interferometry has been considered to be a powerful tool for subsurface structure survey. Seismic interferometry is a method that produces pseudo reflected waveform data by computing the autocorrelation function (ACF) of seismic waveform record. In this study, we estimate the seismic basement structure beneath the northwestern Noto Peninsula from seismic interferometry and microtremor analysis. We examine the reliability of seismic interferometry and microtremor analysis by comparing those results with the results from gravity anomalies and a reflection seismic survey (Sato et al., 2007) in this area.

For seismic interferometry, we use waveform data of the aftershocks of the 2007 Noto Hanto earthquake at 44 seismic stations which are located in the northwestern Noto Peninsula. We apply high-pass filter of 2 Hz to SH component of displacement waveform and set a time window of 10 s after the arrival of S wave to calculate ACF. We make the average ACF by stacking all ACFs at each station. For microtremor analysis, we performed microtremors observation at 44 points where the stations for the aftershock observation were located and calculate H/V spectrum at each station. We estimate the basement structure in the analyzed area by assuming two-layer structure from ACF and H/V spectrum.

For the ACF analysis, it is difficult to identify the dominant peak of ACF for most stations. Especially, we cannot estimate the basement depths where the basement depths estimated from the reflection seismic survey (Sato et al., 2007) are shallower than 100 m. Finally, we obtain the basement depths at 14 of 44 stations. On the other hand, for the microtremor analysis, we can estimate the basement depths at 35 of 44 points. This indicates that the seismic interferometry with ACF is not an effective approach to estimate the basement depths in the northwestern Noto Peninsula.

We compare the basement depths estimated from ACF, H/V spectrum and gravity anomaly each other. These estimates are approximately coincident each other and shows that the basement depth of the Kuwatsuka block is shallower than that of the Saruyama block. Coseismic uplift was observed in the Kuwatsuka block at the 2007 Noto Hanto earthquake. Therefore, the results of this study is coincident with the hypothesis that the activity of active faults on seafloor near the coast causes the uplift of the Kuwatsuka block and makes its basement depth shallower (Hiramatsu et al., 2008).

Acknowledgements: We are grateful to the group for the joint aftershock observations of the 2007 Noto Hanto Earthquake for the use of waveform data and to NIED for the use of the instrument of microtremor observation. We thank Dr. Shigeki Senna for helpful advice.

Keywords: auto correlation function, H/V spectrum, gravity anomaly, geological block structure, the Noto Peninsula

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Retrieval of Green's function in a 3D inhomogeneous medium with nonisotropic source distribution using interferometry

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Seismic interferometry is known to retrieve Green's functions in an elastic homogeneous medium with isotropic source distribution (e.g., Wapenaar and Fokkema, 2006), and is applied to estimate velocity structures using long time series of ambient noises (e.g., Shapiro and Campillo, 2004). However, the realistic noise field might be an inelastic inhomogeneous medium with nonisotropic source distribution, and thus the reliability of retrieval of Green's functions using seismic interferometry should be examined.

We study on the reliability of seismic interferometry in a 3D inhomogeneous structure model of Kanto basin with nonisotropic source distribution. The numerical study on seismic interferometry was conducted by using 3D FDM. We cross correlated the surface responses at two sites with multiple surface sources. We used Yamanaka and Yamana (2006) for the 3D inhomogeneous model of Kanto basin. Nonisotropic source distribution was made by using sources located only on the sea area. We investigated the influence for the cross correlation functions by comparing with that in a homogeneous medium or isotropic source distribution.

In a case of homogeneous medium with isotropic source distribution, we see slight difference between the cross correlation function and Green's functions, but the surface wave component was well retrieved and surface wave velocity compares well with the Green's function. The slight difference might have been caused by the approximations in seismic interferometry (e.g., Kimman and Trampert, 2010). The cross correlation function showed symmetry for positive and negative lagtimes. In a case of homogeneous with nonisotropic source distribution, the cross correlation function shows asymmetry whose surface wave cannot be seen in positive lagtimes. However, the cross correlation functions in negative lagtime compares well with that retrieved with isotropic source distribution, and it showed good agreement in terms of group velocity. These indicate the influence of source distribution on seismic interferometry would be large as indicated in numerous studies (e.g., Tsai, 2010).

In a case of a 3D inhomogeneous model of Kanto basin, the cross correlation function showed asymmetry even with isotropic source distribution. That is, an inhomogeneity complicates wave propagations and then make apparent source distribution nonisotropic even with the isotropic case. Specifically, larger amplitudes in negative lagtimes than that in positive lagtimes indicate that eastern sources became large apparently. Considering the Kanto basin model, Kanto mountains located in western part and Pacific Ocean located in eastern part, where have thick sediment layers, the eastern sources would have excited surface wave significantly, which caused apparent nonisotropic source distribution. Due to asymmetry in the cross correlation function, it does not match with the Green's function. Group velocities also show asymmetry, however, they agrees to that of Green's function. In a case of a 3D inhomogeneous model with nonisotropic source distribution, the cross correlation function shows asymmetry and show less agreement with the Green's function. However, the group velocity shows agreement.

As a result, the retrieval of Green's function using seismic interferometry is strongly influenced by source distributions. Moreover, an inhomogeneity affect to source distribution, it would also be the problem. In a realistic case, therefore, to understand how much isotropy is satisfied is important. Because understanding the source isotropy is tough, it is important to examine the influence considering with realistic applications. However, on group velocity estimations as many applications, the reliability showed good in this study, suggesting the high possibility for reliable applications in seismic interferometry.

Keywords: Seismic interferometry, Green's function, inhomogeneous, isotropic source, 3D FDM

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Estimation of subsurface structure by high density microtremor observations in Kochi Plain

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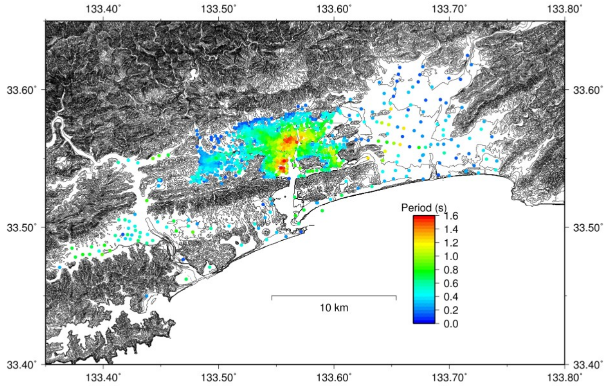
Kochi Plain is located around source region of the great Nankai Earthquake. Strong ground motion is expected in this area, because soft subsoil is widely deposited in Kochi Plain. In this study, we investigate H/V spectra of microtremor in the Kochi Plain. Microtremor study with single station is cheaper, quick and easier way than sampling boring core. It is convenient to reveal horizontal variation of soil/basement structure. We append 213 measurements in addition to previous reported 1041 measurements (Oishi et al., JpGU 2013, SSS35-P02). In total 1254 measurements are used to H/V spectral analysis. Figure shows distribution map of dominant periods by H/V spectral analysis based on microtremor observations in Kochi Plain. In perspective, dominant periods of H/V spectra around northern Urado-Bay region are longer than other regions. According to soil/basement model using boring data, the bedrock depth at this region is especially deep but boring which reaches the bedrock is limited. In contrast, H/V spectral analysis is useful to grasp the extent of region with deep soil/basement boundary. Dominant periods of H/V spectra around western part of Kochi Plain are relatively shorter than Urado region. The damaged areas of the past 2 (1854 and 1946) Nankai Earthquakes match with areas where the dominant period is long and/or the amplification factor is large. High density observations in this region show clear local variations. These are not reflected on current hazard maps or seismic intensity estimation maps. Using H/V spectral analysis based on high density microtremor observation, we are detecting patterns of soil/basement structure which has not be grasped using only boring core data.

Acknowledgement: We thank to Tadashi Hara and Nobuaki Kitamura, Kochi University and NEWJEC Inc. for providing their data.

Keywords: microtremor, H/V spectral ratio, subsurface structure, Kochi Plain



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Recent Geological Interpretation of A Liquefied Area: A Case Study in Urayasu City, Japan (1)

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[1]Kanto Natural Gas Development Co., Ltd, [2]JAPEX, [3]No affiliation, [4]Chiba-kita High School, [5]NTC Consaltants Co., Ltd., [6]Chiba-nishi High School, [7]Urayasu High School, [8]Chishirodai High School, [9]Earth System Science Co., Ltd.

At Urayasu High School (Urayasu City, Chiba Prefecture), where one of authors worked, the 2011 Great East Japan Earthquake caused the formation of two large open cracks from which large amounts of sand and water erupted as a result of soil liquefaction (Kusunoki et al., 2011). The objectives of this study were to investigate both the cause and the mechanism of this phenomenon. The site is located on reclaimed land, and a survey of the site's subsurface geology was carried out by hand auger boring and simple dynamic cone penetration testing to observe the stratigraphy of the reclaimed bed. Aerial photographs of the different stages of the reclamation were also used for analysis.

The survey area was the school grounds, which are located several hundred meters from the former seashore. Holocene deposits were situated at a depth of approximately 3-4 m. Two large open cracks formed in the ground: crack '1' in the NNE-SSW direction and crack '2' in the WNW-ESE direction. Beneath the cracks, we found row of piles from the original ground reclamation work. These rows of piles had been laid underground, and the reclaimed bed consisted of sand and silt. The cracks appeared to be due to the difference in vibrational characteristics between the opposite sides of each crack. Also, the facies of the reclaimed bed were notably different on the opposite sides of each crack. In the cross section of crack '2', the Nd-value*was very large on the northeast side (Nekozane River side) but relatively smaller on the southwest side. In the cross section of crack '1', the facies of the reclaimed bed from approximately 2 m above to the top of the Holocene deposits were sandy on the western side relatively large Nd-value, but on eastern side mainly formed of silty material recorded almost 0.

Analysis was conducted using aerial photographs and revealed that both cracks '1' and crack '2' were located on the same discontinuity in the reclamation work history, both spatially and temporally. Therefore, the survey area contained three sections of reclaimed land demarcated by the two cracks. Moreover, a fourth section consisted of Holocene deposits. Chronologically, the survey area contained (a) 'Kaimenka-tochi' **(Urayasu City, 1985), (b) reclaimed land composed of sand and silt dredged from the seabed, and (c) the surrounding embankment. The reclamation process differed between areas (a) and (b). Area (b) was the widest and was typical of reclaimed land. Area (c), in contrast, was not constructed by dredging sand and silt from the seabed. Crack '1' was located between areas (b) and (c), and crack '2' was located between areas (a) and (b).

Therefore, the occurrence of these cracks seems attributable to discontinuities in the reclamation history. This case shows that recognizing the geological and historical processes of both the Holocene deposits and the reclaimed land is an important aspect of disaster prevention.

*Nd-value is brought by Dynamic Cone Penetration Test, which has the following conditions: a slide hammer with a weight of 5kg falling through a distance of 50cm, and diameter of 2.5cm cone. The number(i.e. Nd-value) of blows needed for the cone to penetrate each 10cm is recorded.

**'Kaimenka-tochi' means land below sea level literally. Before reclamation, it was located in front of seashore, and it was in the possession of the private owner. and was used to reed cultivation etc.

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