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APPLICATION OF MICROTREMOR MEASUREMENT FOR ESTIMATE OF OVERALL STIFFNESS OF LEVEES

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ABSTRACT: This study explores the feasibility of estimating overall shear wave velocity for levees to detect weak sections by using microtremor measurement. Microtremor measurement is carried out on the crest and near the toe of the levee embankment simultaneously by placing servo-type velocity sensors perpendicular to the levee axis. Then, transfer functions are calculated using the horizontal motions. Finally, overall shear wave velocity structure is identified so that the peak frequency of the transfer function and the fundamental frequency of finite element model of the levee that has the same cross section coincide. The identified shear wave velocities are mostly consistent with shear wave velocities estimated based on SPT blow counts. Hence, this method is feasible to detect weak sections along levees.

Keywords: Levee, Microtremor measurement, Inner structure, Overall stiffness

1. INTRODUCTION

The 2011 off the Pacific Coast of Tohoku Earthquake caused a lot of damage to levees over a wide area of Tohoku and Kanto districts. A total number of 2,134 levees were reportedly damaged (the details were 1,195 from Tohoku district as of April 21, 2011 [1] and 939 from Kanto district as of July 31, 2011 [2]) among levees under jurisdiction of the Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT), Japan. Damage occurred simultaneously in wide spread regions of Tohoku and Kanto districts.

Until the occurrence of this disaster, we may have had an idea in Japan that damaged levee embankments can be repaired simply, even if they are damaged by an earthquake, since earth structures can be relatively easily restored within the time of little flooding risk. However, it became clear that this idea is not applicable to a gigantic earthquake event because damage occurred over a wide spread area simultaneously beyond the capacity of construction work of the devastated area’s community. Therefore, it is of the utmost necessity to both efficiently and rapidly carry out seismic improvements of levees, while evaluating their seismic performance when subjected to strong ground motions.

For spreading linear-shape earth structures such as levee embankments, seismic performance is usually evaluated for a representative cross section selected by performing screening in the first stage of seismic design. However, this is not an easy task and is cost prohibitive since we need to examine every cross section along the river. An acceptable method would be a simple one which is capable of evaluating its seismic performance at every section along the river. The most significant problem lurking in the evaluation of seismic performance of levees may be that inner structure of a levee embankment is unclear for most of the levee cross sections. This is basically due to historical reasons. In Japan, levee embankments have commonly been raised over time to become the current structure for over 100 years. Detailed information regarding materials and method of compaction from a long time ago is missing and unknown.

As for investigation method of inner structure of levees, drilling and geophysics-based methods are possible choices. Boring is the most direct and simple method, however, it is expensive to conduct for long levees. Cone penetration test is another direct method becoming popular for the purpose. Regarding geophysics-based methods, an electromagnetic wave method and surface wave method seems to be two representative methods. The electromagnetic wave method is capable of detecting cavities and embedded objects by using electromagnetic pulse [3]. Frequency domain electromagnetic method measures distribution of resistivity along the levee. Based on the correlation between resistivity and condition of soils, it may be able to detect weak section of levees [4]. A surface wave method can detect shear wave structure of levees by measuring surface waves traveling along the levee [3]. Multi-channel analysis of surface waves (MASW) is widely used as a noninvasive assessment method of earthen levees, and it is applied many cases (e.g., [5]). In addition to that, an integrated geophysical investigation consists of multi-channel surface wave dispersion measurements, capacity-coupled resistivity measurements, and additional multi-

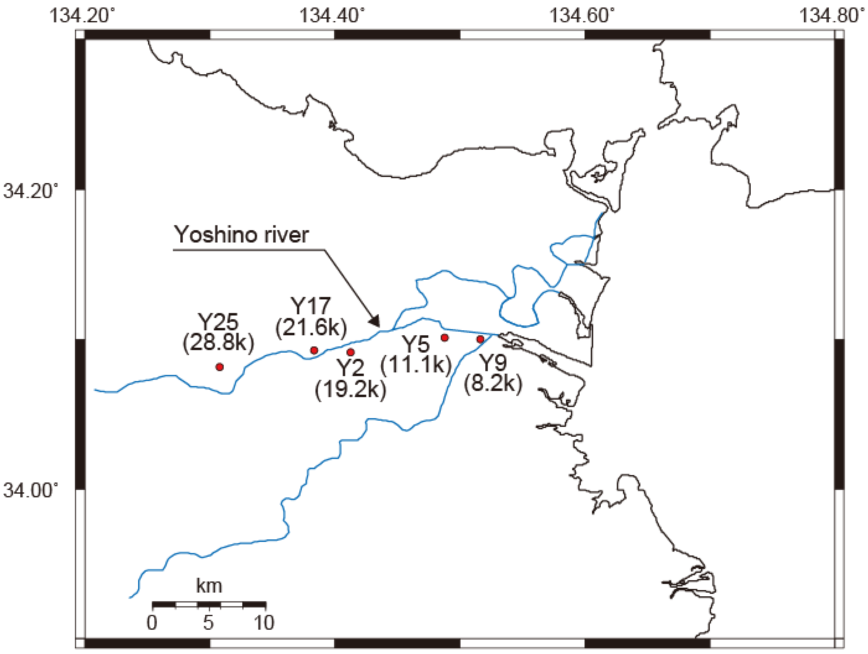


Fig.1 Microtremor observation stations along Yoshino River

frequency electromagnetic survey has been developed by Inazaki et al.[6]. An even simpler method that can detect relatively weak cross sections being densely applied along the levee is desirable.

This study explores the possibility of applying microtremor measurements for estimating overall inner properties of a levee, especially paying attention to overall shear wave velocity of the levee to detect weak sections along the levee. Measurement was conducted along Yoshino river levee from the river mouth to approximately 30km upstream. At these sections, SPT-N value data was provided by the MLIT Tokushima office.

2. MICROTREMOR OBSERVATION AT LEVEE SITE

2.1 Historical Background of Yoshino River Levee

Yoshino River is one of the longest rivers in Japan, categorized as a class A river which has a length of 194km. There are three major construction stages for this levee with the first one dating back to 1907 [7]. Over more than 100 years, the present day levee structure was gradually formed. In the first stage of construction, compaction was conducted by hand, hence, most likely being the cause of weak levee section due to weak compaction.

2.2 Observation Site

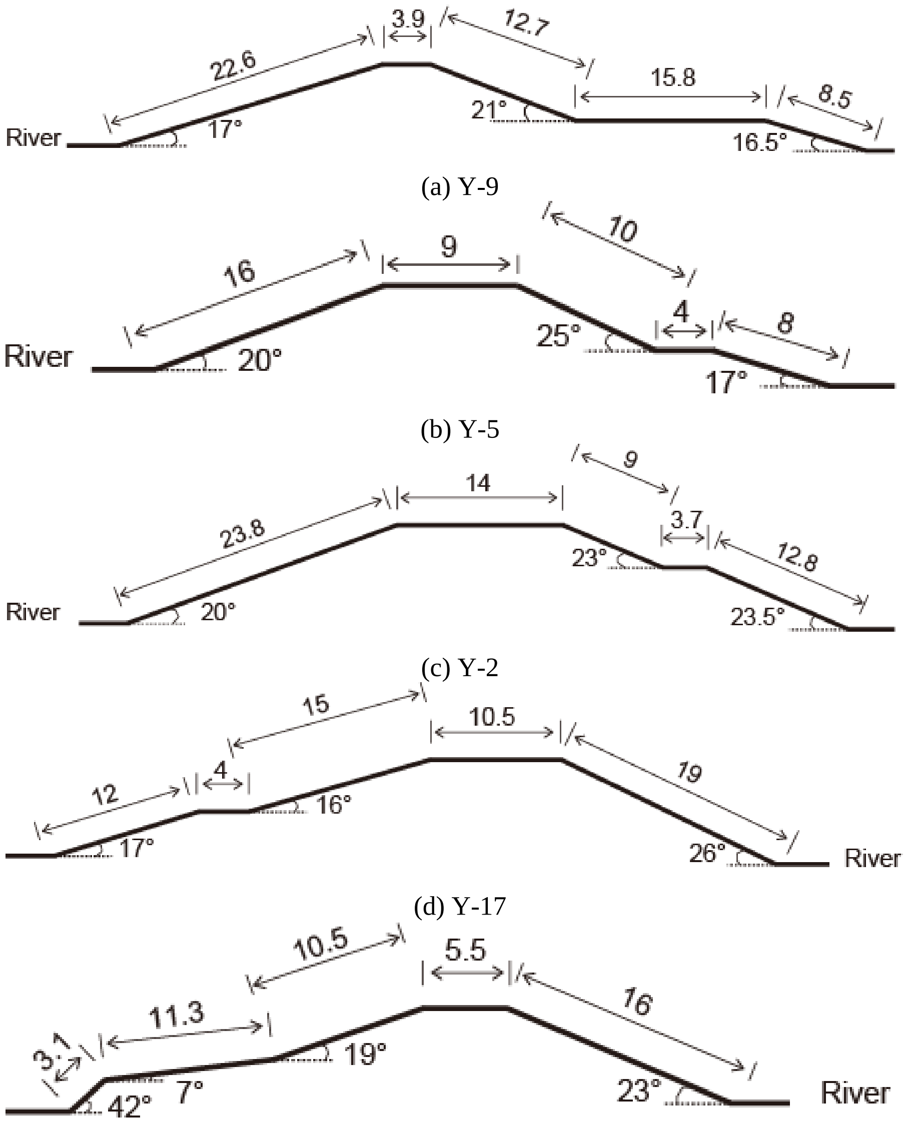
SPT tests have been densely conducted along the Yoshino River levee by MLIT Tokushima. At some limited number of cross sections, excavations of levee were conducted, in order to construct levee facilities such as sluice gates. Hence, five observation points close to the excavated segments were selected along Yoshino River so that we could view the inner structure of the levee as shown in Fig. 1. To select the observation points, attention was paid not to include any excavated segments as such segments have no remaining original levee inner structure after backfilling. Distances from the river mouth to the observation sites range from approximately 8 km to 29 km.

2.3 Surveyed Cross Sections of Yoshino River Levee

Although blue prints of levee cross sections are available for every 200 meters, levee shapes differ even within a 200 segment. Therefore, a survey was conducted by the author and his colleagues using tape measure and digital clinometer. Cross sections of levees at each observation point are shown in Fig. 2, looking from the upstream to downstream direction.

2.4 Method of Microtremor Observation

For site amplification problem of soft soil deposit, transfer functions are calculated by the ratio of Fourier spectrum at the ground surface to outcrop bedrock. Analogous to this problem, Fourier



(a) Y-9

(b) Y-5

(c) Y-2

(d) Y-17

(e) Y-25

Fig.2 Cross sections of levee (unit in meters)

spectral ratio of crest to the free-field ground surface is considered.

Microtremors were simultaneously observed at the crest and toe of the levee embankment as shown in Fig. 3. Placing a servo velocity-meter (Tokyo Sokushin, VSE-15D) perpendicular to the levee axis, horizontal component was observed in order to calculate the transfer function between the bottom and top of the levee embankment. Sampling frequency was 100(Hz), and each observation continued for 300 seconds. It is often the case that the crest area is used as a road for vehicles, hence uncontaminated signal sections were carefully extracted from the unprocessed recorded signals in order to avoid traffic noise. Although the free-filed condition is ideally situated some distance from the toe of the levee embankment, free-field microtremor

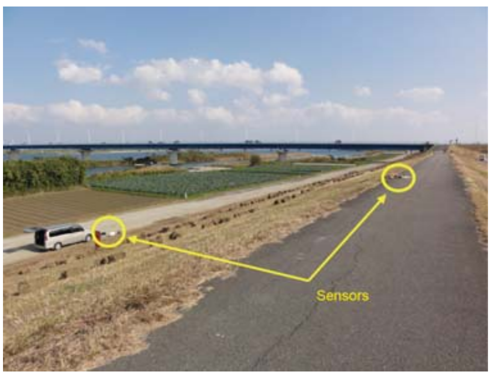


Fig.3 Microtremor measurement at levee site

measurements were observed near the toe (only several meters away from the toe) due to observational constraint conditions. Observations were carried out avoiding windy and rainy days.

3. ESTIMATION OF OVERALL SHEAR WAVE VELOCITY OF LEVEE

3.1 Calculation of Transfer Function

The transfer function can be visualized as representing the characteristics of a system that receives an input *x* which is modified to an output *y*. In the context of surface soil deposit response system, input *x* would be outcrop bedrock motion and *y* would be free-field motion at the surface of the soil deposit. For the levee-ground response system, analogous to surface soil response system, input *x* would be ground motion near the toe of the levee and *y* would be levee crest motion. The transfer function can be calculated from spectral density functions as follows:

$$\left|H(f)\right| = \sqrt{\bar{S}_{yy}(f)/\bar{S}_{xx}(f)} \quad (1)$$

where $\bar{S}_{xx}(f)$ and $\bar{S}_{yy}(f)$ represent smoothed auto power spectral density functions of the input and output signals. A Parzen window of 0.4(Hz) bandwidth was used for smoothing the power spectrum in the frequency domain.

3.2 Coherence

In this study, transfer functions are calculated using microtremors, not earthquake ground motion, observed at the crest and toe of the embankment as a pair. Hence, these signals need to be correlated. To pay attention to correlation of these records, coherence functions are calculated. Here, coherence function is defined as follows:

$$\gamma^2(f) = \frac{\left|\bar{S}_{xy}(f)\right|^2}{\bar{S}_{xx}(f)\bar{S}_{yy}(f)} \quad (2)$$

where $\bar{S}_{xy}(f)$ is the smoothed cross spectral density function (smoothing was conducted by the same method as before). Coherence function becomes smaller when it moves to a high frequency range and when two signals are less related to each other. The average coherence of pairs of white noise signals is approximately 0.25 ±0.04 for a type of smoothing [8]. For frequency beyond a certain frequency, coherence converges towards 0.2-0.3, as phase variations between the records in the pair are essentially stochastic. Transfer function amplitude would similarly be expected to be highly random for the same frequency range. Accordingly, we consider the transfer function at such frequencies to have little significance.

3.3 Calculation of H/V Spectral Ratio

Horizontal to vertical spectral ratio is called the H/V spectral ratio. By looking at the peak frequency of the H/V spectral ratio, predominant frequency of ground can be estimated [9]. This information can be effectively referred to when we need to choose inherent frequency of the levee from the peak frequencies of transfer functions.

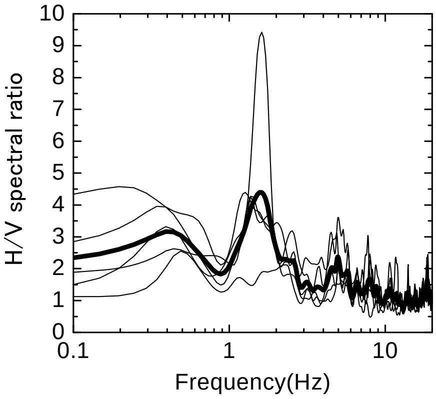
3.4 Identification of overall shear wave velocity of the embankment using FE model

Once significant peak frequency is found from the transfer function calculated from the pair of records observed at the crest to the toe. We consider this to be the system frequency. When preparing the two dimensional finite element model which has the same outlines as that of the levee, having overall shear wave velocity ($\bar{V}_S$) and with rigid base, the $\bar{V}_S$ value is identified so that the fundamental frequency of the FE model coincides with the peak frequency of the transfer function of levees. Due to the rigid base assumption of levees, this method may underestimate $\bar{V}_S$ a little.

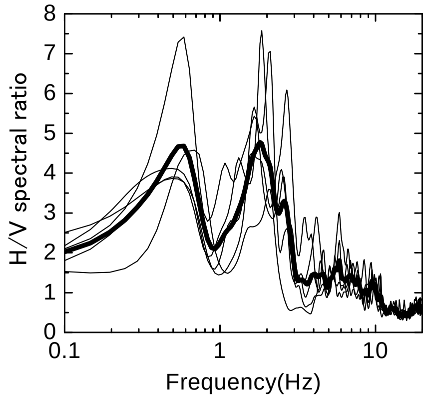
4. Results

4.1 H/V Spectral Ratio of the Ground

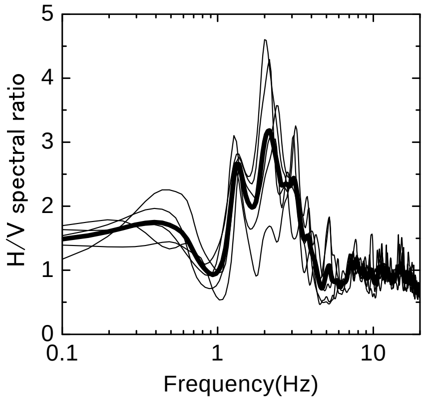
Horizontal to vertical spectral ratio of the ground is shown in Fig. 4(a) to 4(e). Five segments of 20.48(sec) data are extracted from the original recordings that consist of three components (two horizontal and one vertical). Next, horizontal to vertical spectral ratios are calculated for each component as shown by the thin lines in Fig. 4. To obtain the horizontal spectrum, square root of sum of squares of two horizontal components (transverse and axial) are calculated. Then, these five spectral ratios are averaged in order to determine the final H/V spectral ratio as shown by the thick line. Predominant frequencies of the ground at each site can be evaluated from these results. For example, predominant frequency of Y9 site is 1.56(Hz) from the peak frequency as can be seen in Fig.4(a). Predominant frequency of sites Y5 and Y2 are recognized as 1.81(Hz) and 2.15(Hz), respectively. Regarding site Y17, two peaks can be seen at 2.44(Hz) and 5.66(Hz). Finally, for Y25, predominant frequency is assumed to be either 0.59(Hz) or 3.03(Hz), however, a peak frequency of lower than 1(Hz) was not taken into account



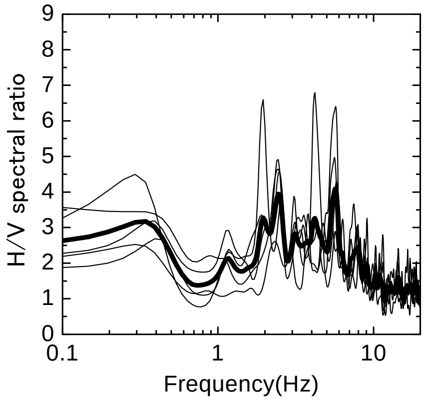
(a) Site Y9



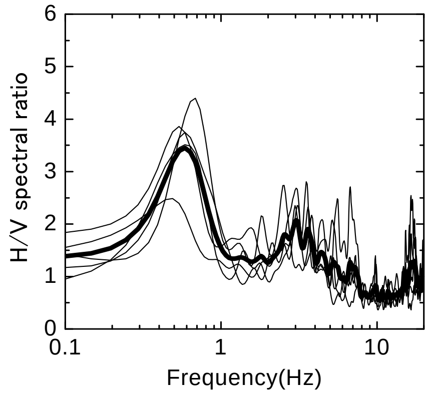
(b) SiteY5



(c) Site Y2



(d) Site Y17



(e) Site Y25

Fig.4 H/V Spectral Ratio (thick line is average of other thin lines)

since the peak probably is due to reflection of deep bedrock, and it does not have any effect on transfer functions of the levee system.

4.2 Power spectrum density functions, coherence functions and transfer functions

Analytical results of microtremor measurements are shown in Fig.5(a) to Fig.5(e). The upper frame of each figure shows power spectral density function of microtremors obtained from the crest and near the toe of the levee embankment. Shown in the middle of these figures are coherence functions. The bottom ones are transfer functions calculated from the power spectral density functions based on Eq.(1). Looking at Fig.5(a) (site Y9), it can be seen that coherence function gradually decreases as

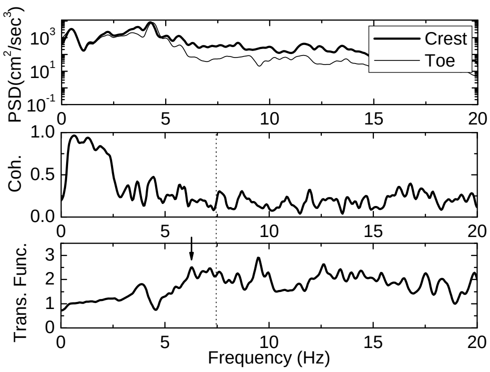


Fig.5(a) Power Spectral Density Function, Coherence Function and Transfer Function at Y9

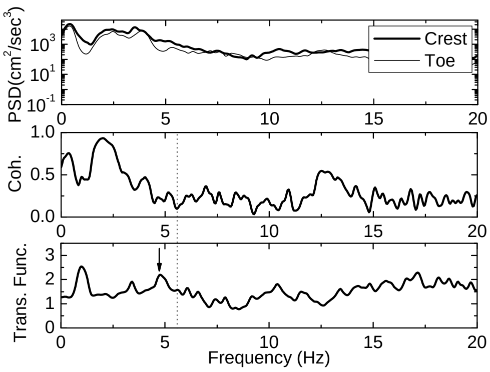


Fig.5(b) Power Spectral Density Function, Coherence Function and Transfer Function at Y5

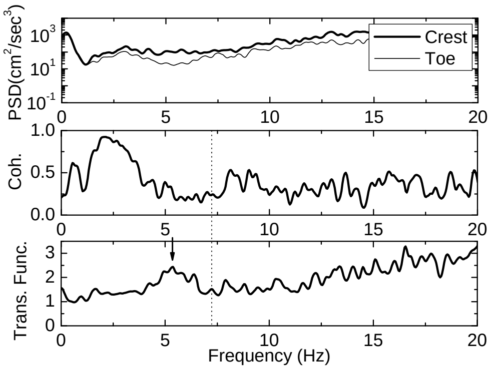


Fig.5(c) Power Spectral Density Function, Coherence Function and Transfer Function at Y2

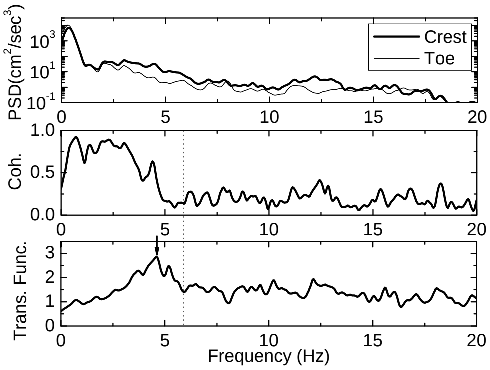


Fig.5(d) Power Spectral Density Function, Coherence Function and Transfer Function at Y17

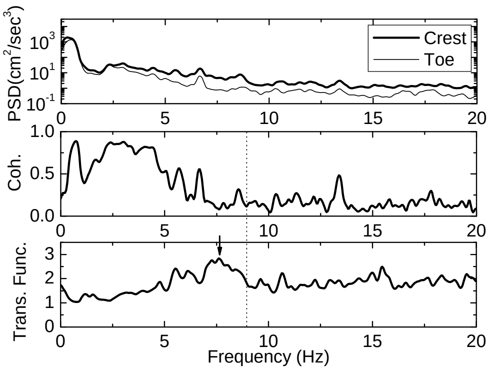


Fig.5(e) Power Spectral Density Function, Coherence Function and Transfer Function at Y25

frequency becomes higher up to about 7.5(Hz) and fluctuates around a constant value beyond that frequency. Hence, attention is only paid to the transfer function below 7.5(Hz).

Peak frequency at about 6.3(Hz) is considered to be the inherent frequency of the levee (shown by an arrow). Note that this frequency is different from evaluated predominant frequency of the site (1.56Hz). In Fig.5(b) (Y5), coherence reduces up to 6(Hz) and fluctuates around a constant value beyond that frequency. Transfer function below 6(Hz) is noted here. Inherent frequency of the levee is assumed to be 4.79(Hz) shown by the arrow. Looking at Fig.5(c) (Y2), peak frequency of transfer function at 5.37(Hz) is likewise considered to be the inherent frequency of the levee. At the site Y17 shown in Fig.5(d), peak frequency is recognized to be 4.59(Hz) which is assumed to be the inherent (natural) frequency of the levee. Finally, in Fig.5(e), 7.62(Hz) is considered to be the natural frequency of the levee as the coherence function becomes a state fluctuating around a constant value beyond about 9(Hz). Those results are summarized in Table 1.

4.3 Identification using finite element model

The final process is to identify the overall shear wave velocity of the levee which can be

Table 1 Summary of Results

Site	Distance from river mouth	Predominant frequency of the ground (Hz)	Peak frequency from transfer functions (Hz)	Identified overall shear wave velocity (m/sec)	N-Value of levee and soil
Y9	8.2 km	1.56	6.30	126	2 ~ 5 Sandy silt
Y5	11.1 km	1.81	4.79	85	2 ~ 4 Sandy silt
Y2	19.2 km	2.15	5.37	142	5 ~ 12 sand and gravel
Y17	21.6 km	2.44, 5.66	4.59	121	5 ~ 8 Sand with gravel
Y25	28.8 km	3.03	7.62	163	7 ~ 18 Gravel and Sand

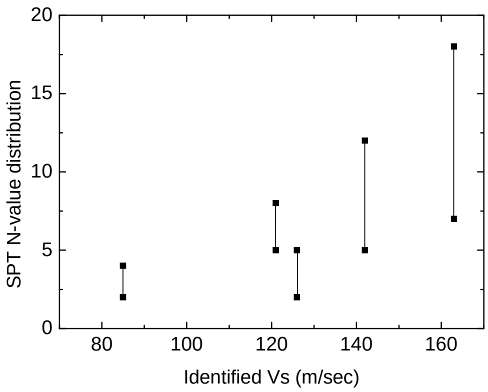


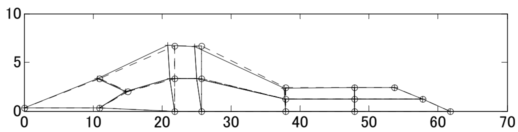
Fig. 6 SPT-N value and Identified Vs at each site

approximately estimated using SPT-N values correlated by the relation [10]:

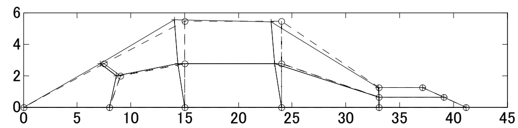
$$Vs = 80N^{1/3} \text{ for sand} \quad (3)$$

Ranges of SPT blow counts distributed along the depth of the levees are shown in Fig.6.

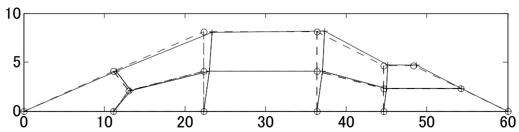
Finite element models of each site are prepared as shown in Fig. 7. As described before, inner shear wave velocity profiling of the levee is assumed to be constant (hence, identified Vs is overall value denoted by $\overline{V}_S$) on a rigid base. $\overline{V}_S$ of the levee is identified so that the fundamental frequency of the levee approximately coincides with the peak frequency obtained in the former section, assuming soil density as 1800(kg/m^3) and Poisson's ratio as 0.45. As a result of identification, for example, $\overline{V}_S$ value of 126(m/sec) is obtained for the site Y9. Identified $\overline{V}_S$ values are summarized in Table 1. Comparing these identified results with those SPT-N values shown in Fig.6, it is recognized that $\overline{V}_S$ values identified by using microtremor measurement are



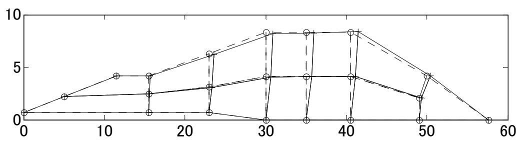
(a) Y9 (1st mode, $\overline{V}_S$ =126m/sec)



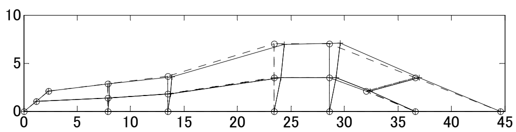
(b) Y5 (1st mode, $\overline{V}_S$ =85m/sec)



(c) Y2 (1st mode, $\overline{V}_S$ =142m/sec)



(d) Y17 (1st mode, $\overline{V}_S$ =121m/sec)



(e) Y25 (1st mode, $\overline{V}_S$ =163m/sec)

Fig.7 Identified Finite Element Model (1st mode)

by and large consistent with the SPT evaluation. Although the obtained $\overline{V}_S$ provides an overall shear wave velocity of the inner structure, the identified $\overline{V}_S$ may be underestimated as the numerical model used for identification (FE model) assumed as a rigid base.

Some of the figures were created by using GMT(Generic Mapping Tools).

5. CONCLUSIONS

This paper explored the feasibility of application of microtremor measurement to estimate of overall shear wave velocity for levee embankments. Microtremors were measured at the crest and near the toe of the levee simultaneously by placing velocity sensors perpendicular to the levee axis. Transfer functions were then calculated using the pair of horizontal motions. Finally, overall shear wave velocity structure of levee was identified so that the peak frequency of the transfer function and the fundamental frequency of the finite element model of the levee that had the same cross sections coincided. The identified shear wave velocities ranged from 85(m/sec) to 163(m/sec), which seemed to be appropriate. It was found that the identified shear wave velocity is mostly consistent with the ones estimated by using SPT blow counts, e.g. identified smallest shear wave velocity of 85(m/sec) corresponds to smallest SPT-N value distribution N=2-4 and largest shear wave velocity of 163(m/sec) corresponds to largest SPT-N value distribution N=7-18. Hence, this method is expected to be feasible to detect weak sections along levees.

6. ACKNOWLEDGMENTS

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