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Comparison of Monitored and Estimated Microtremor H/V Spectra after the Large-scale Earthquakes at a Ground Disaster Site in Fusa District, Abiko City, Japan

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ABSTRACT

Recovery process of shear modulus of subsurface soil after the 2011 Tohoku Earthquake sequence at a ground disaster site in Fusa District, Abiko City, Japan, was revealed by intermittent measurements of microtremor for 1,000 days before/after the 2011 main shock. The recovery process was then simulated based on dynamic FEM analyses taking into account the generation and dissipation of excess pore water pressure with estimated strong motions for the main shock and two large aftershocks. Microtremor H/V spectra were simulated by applying a random excitation for the same FEM model with decreased shear modulus corresponding to time-dependent excess pore water pressure. The observed time-dependence of the peak frequency of microtremor H/V spectra was reproduced quite accurately in the simulation, which indicates that the time-dependence of shear modulus was controlled by the generation and dissipation of excess pore water pressure.

Introduction

Previous studies have reported a phenomenon in which shear modulus of soil is decreased during a large earthquake and then gradually recovers over a time interval of several months (e.g., Anderson and Woods, 1976; Anderson and Stokoe, 1978; Arai et al., 2006). It is important to fully understand such phenomenon, because it is related to the dissipation of excess pore water pressure and hence to a potential long-term deformation of soil after a large earthquake. In spite of its importance, there have been relatively few field data with respect to the recovery process of shear modulus of soil after a large earthquake. In addition, there have been relatively few analytical studies to simulate the recovery process.

During the March 11, 2011 off the Pacific coast of Tohoku Earthquake (hereafter referred to as the "2011 Tohoku Earthquake"), extensive liquefaction occurred in Fusa District, Abiko City, Japan, which is located in the Tone river basin (e.g., Kanto Regional Development Bureau, Ministry of Land, Infrastructure, Transport and Tourism and the Japanese Geotechnical Society, 2011; Koseki et al., 2012; Hata et al., 2012a). The authors had a chance to conduct intermittent measurements of microtremor for 1,000 days before/after the 2011 main shock at a site fairly close to the liquefied site in Fusa District. In Fusa District, both of liquefied sites and non-liquefied sites were confirmed, based on the result of author's reconnaissance survey on 13 March 2011, the trace of the soil liquefaction such as boil sand is not confirmed at the site of

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interest (Hata et al., 2014a).

In this article, the recovery process of the shear modulus of silty soil at the site was revealed based on the time-dependent peak frequency of the microtremor H/V spectra (Hata et al., 2014a; 2014b). Then the recovery process was simulated based on dynamic FEM analyses taking into account the generation and dissipation of excess pore water pressure (Iai et al., 2011; Ueda et al., 2014) with estimated strong motions for the main shock and two large aftershocks (Hata et al., 2014c). Microtremor H/V spectra were simulated by applying a random excitation (Lachet and Bard, 1994) for the same FEM model with decreased shear modulus corresponding to time-dependent excess pore water pressure. The observed time-dependence of the peak frequency of microtremor H/V spectra was reproduced quite accurately in the simulation, which indicates that the time-dependence of shear modulus was controlled by the generation and dissipation of excess pore water pressure.

Observed Microtremor H/V spectra

The microtremor measurement was performed at a site no more than 200 m away from a liquefied site with extensive sand boils in Fusa District, Abiko City, Japan. At the microtremor site, a standard penetration test was carried out in November, 1978 and revealed a subsurface soil consisting mainly of silt as shown in Figure 1 (Ooi and Fujiwara, 2013). The initial measurement was conducted 41 days before the 2011 main shock. After the main shock, the earliest measurement was carried out on March 13, that is, only 2 days after the main shock. Then the measurement was carried out intermittently until 1,000 days after the main shock. Two large aftershocks occurred in the time interval, namely, the March 11, 2011 off Ibaraki Earthquake and the April 11, 2011 Hamadori, Fukushima, Earthquake. For details of the measurement (instrument, procedure, etc.), refer to Hata et al. (2014a).

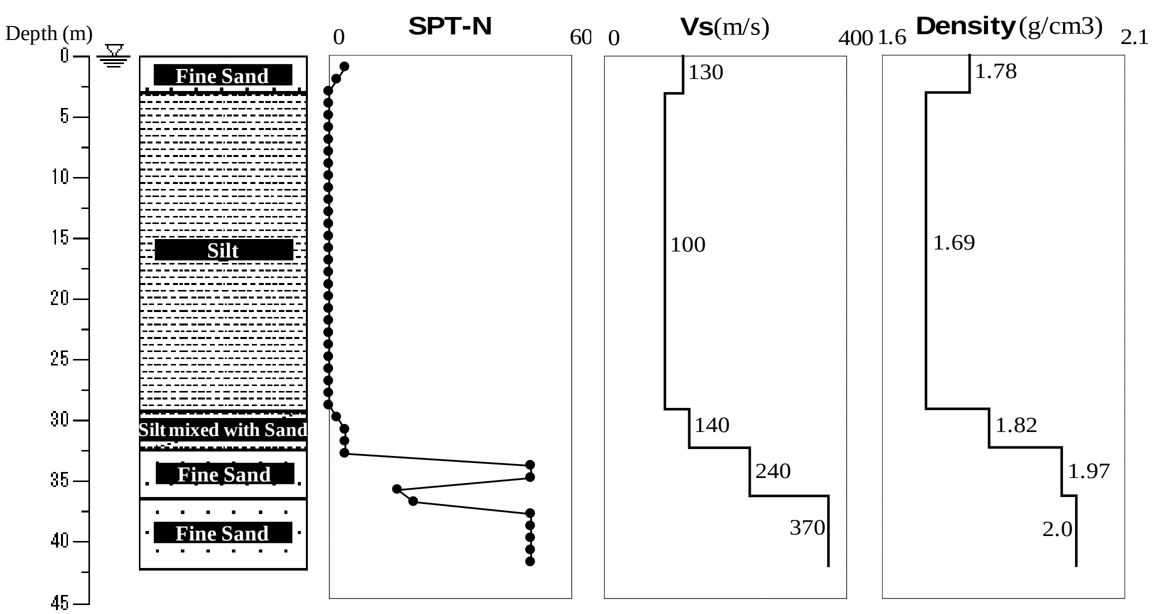

Figure 1. Soil profile from engineering bedrock to ground surface at the site of interest

The comparison of the microtremor H/V spectra before and after the 2011 main shock is shown in Figure 2. The procedure to calculate the H/V spectra is described in Hata et al. (2014a).

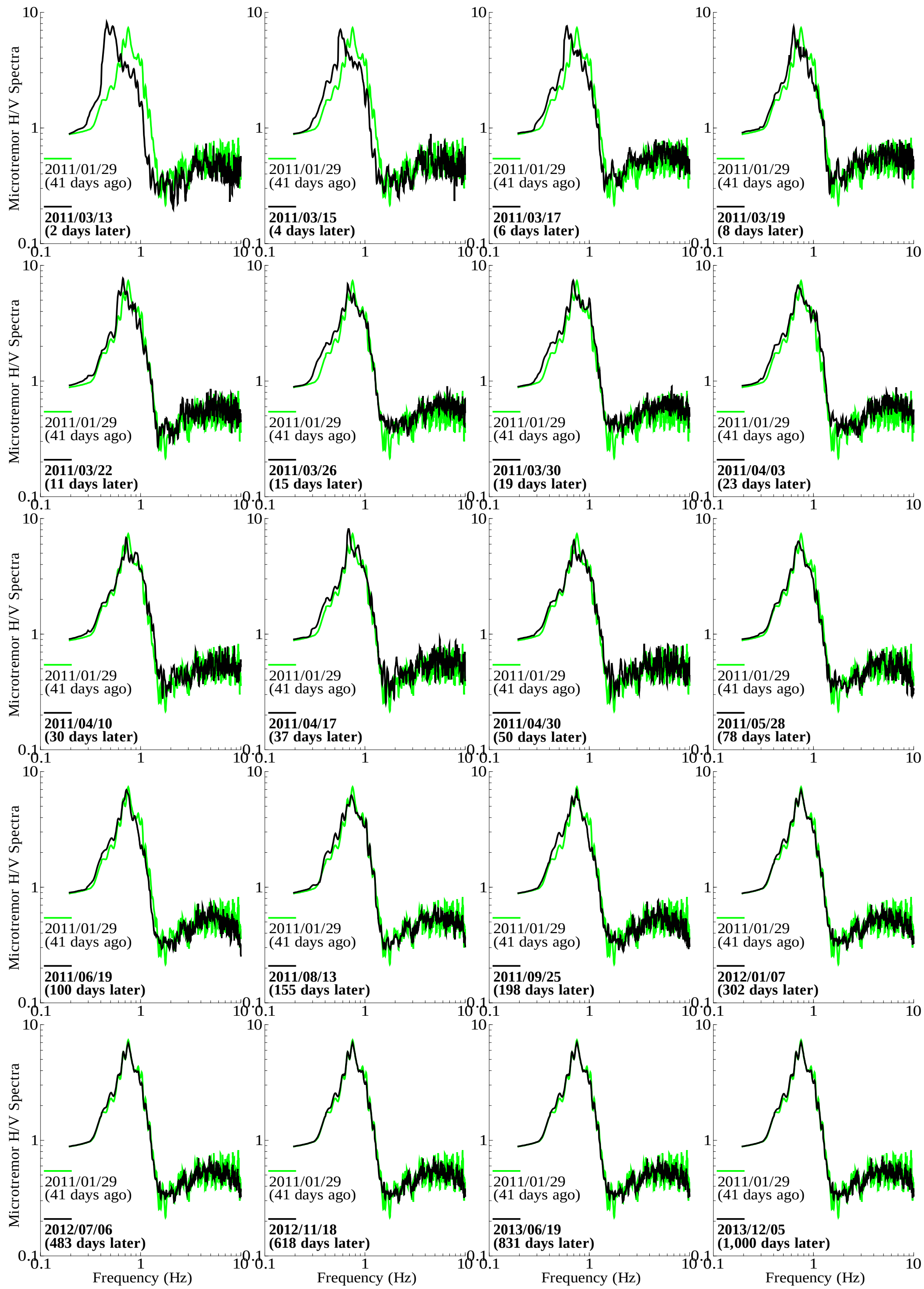

Figure 2. Comparison of microtremor H/V spectra before and after the 2011 main shock

Figure 2 clearly shows the time dependence of the peak frequency of the microtremor H/V spectra. The peak frequency just after the main shock was significantly lower than the initial peak frequency before the main shock, indicating the decrease of the shear modulus of sub-surface soil. Then the peak frequency gradually increased and approached to the initial value, indicating the recovery of the shear modulus. The H/V spectrum 1,000 days after the main shock was almost identical to that before the main shock. Thus, the recovery process of the shear modulus of subsurface soil was clearly documented in the observed microtremor H/V spectra.

Figure 3 plots the time-dependence of the peak frequency of the observed microtremor H/V spectra after the 2011 main shock divided by that before the main shock. In Figure 3, the ratio gradually increased after the main shock and reached almost 1.0 in about 200 days after the main shock. The effect of the April 11 Hamadori Earthquake was also evident. The time-dependence of the peak frequency of the microtremor H/V spectra should mainly be controlled by the generation and dissipation of excess pore water pressure in the silty layer. In the next chapter, in order to confirm this hypothesis, the observed time-dependence of the peak frequency of the microtremor H/V spectra will be simulated based on dynamic FEM analyses taking into account the generation and dissipation of excess pore water pressure in the silty layer.

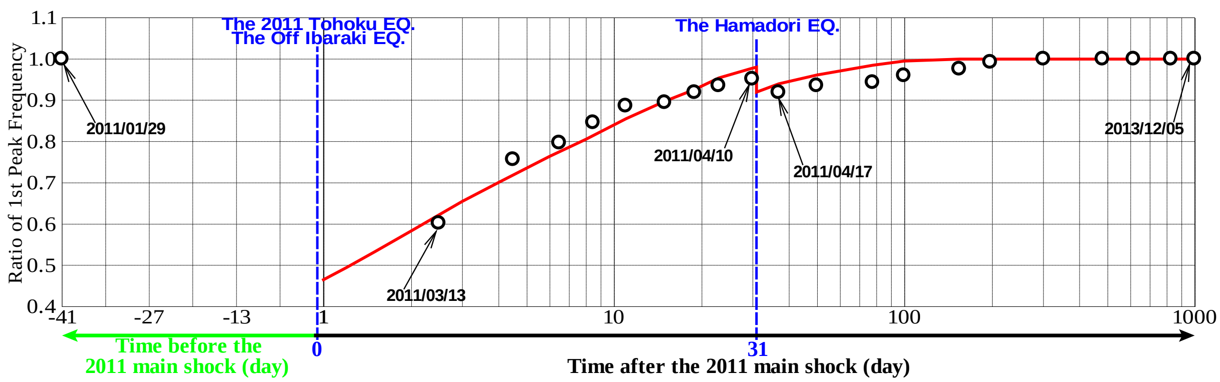

Figure 3. Peak frequency of observed and simulated microtremor H/V spectra

Simulation of Recovery Process

Effective Stress Analysis

We simulated the recovery process based on dynamic FEM analyses taking into account the generation and dissipation of excess pore water pressure (Iai et al., 2011; Ueda et al., 2014) with estimated strong motions for the main shock and two large aftershocks (Hata et al., 2014c). The input earthquake motions were estimated based on the site-effect substitution method (Hata et al., 2011). A 2-dimensional FEM model was developed for the analysis as shown in Figure 4. The model covers 1,000 m in the horizontal direction and 36.3 m in the vertical direction. A total of 29,750 finite elements with 30,630 nodes were used. The element size was chosen to allow response frequency components up to 10 Hz. To represent the shear deformation of soil, the multiple simple shear mechanism represented by a hyperbolic stress-strain relationship was considered. To represent the dilatancy of soil, so called the “Cocktail Glass Model” (Iai et al., 2011) was used. The model parameters for the subsurface ground consisting mainly of a silty layer were determined by Hata et al. (2014b), based on the results of past geotechnical investigations conducted at the site, including PS logging and standard penetration tests (e.g., Ooi and Fujiwara, 2013; Abiko City, 2013).

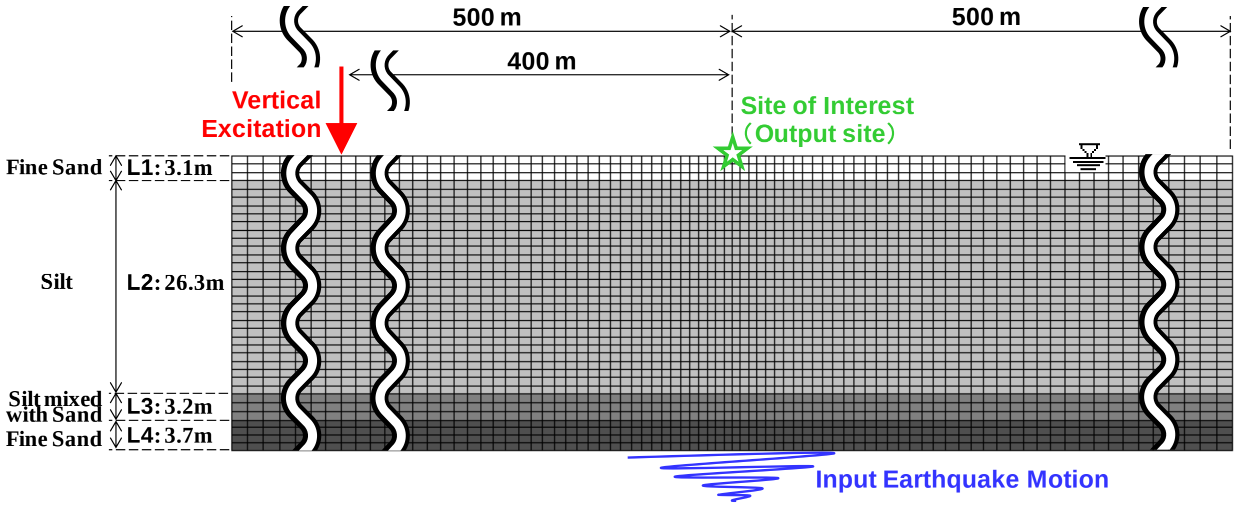

Figure 4. Dynamic FEM model for microtremor and earthquake motion

The input earthquake motions at the bottom of the analysis domain (i.e., the engineering bedrock) were assigned for one direction (N-S or E-W component). The estimated waveforms at the bedrock outcrop at the site of interest for the 2011 main shock and two large aftershocks were used (see Figure 5). The waveforms with the duration of 150.0 s shown in Figure 5 were used for the earthquake response analysis. The side boundaries of the calculation domain were idealized using viscous dampers to allow for incoming and outgoing waves from/to the free-fields. The time integration was done using the Wilson-θ method (θ = 1.4). The Rayleigh damping (α=0, β=0.0009) was used to ensure stabile time integration. The initial conditions were obtained by performing a static analysis with gravity using the same constitutive model used for the earthquake response analysis.

The detailed procedure for the effective stress analysis was as follows: (1) A nonlinear earthquake response analysis was carried out for the estimated input ground motion in the N-S or E-W component due to the 2011 main shock (see Figure 5(a) and Figure 5(b)). After the earthquake response analysis, a consolidation analysis considering the dissipation of excess pore water pressure was carried out for 25 minutes until the off Ibaraki Earthquake occurred. (2) A nonlinear earthquake response analysis was carried out for the estimated input ground motion inthe N-S or E-W component due to the off Ibaraki Earthquake (see Figure 5(c) and Figure 5(d)) based on the initial stress condition due to the results of the previous analysis. (3) The earthquake response analysis was followed by a consolidation analysis considering the dissipation of excess pore water pressure for 31 days until the Hamadori Earthquake occurred. (4) A nonlinear earthquake response analysis was carried out for the estimated input ground motion in the N-S or E-W component due to the Hamadori Earthquake (see Figure 5(e) and Figure 5(f)) based on the initial stress condition due to the results of the previous analysis. (5) The earthquake response analysis was followed by a consolidation analysis considering the dissipation of excess pore water pressure for 969 days until the end of the microtremor measurement.

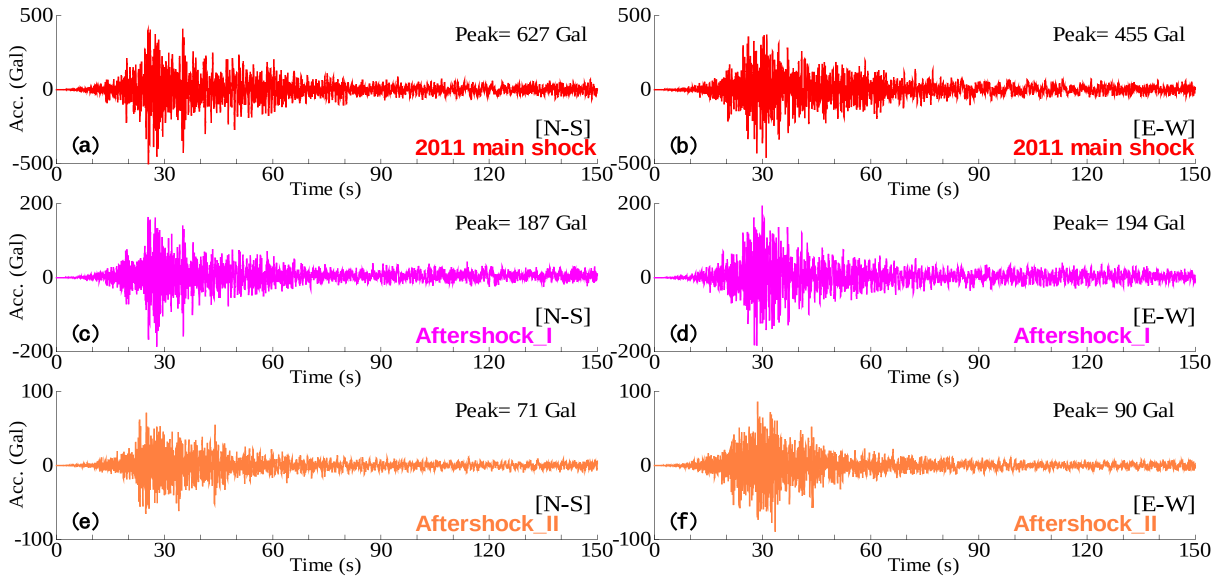

Figure 5. Input earthquake motion

Simulation of Microtremors

On the other hand, simulations of microtremors were conducted by applying a random excitation (Lachet and Bard, 1994) for the same FEM model but with decreased shear modulus corresponding to time-dependent excess pore water pressure. Here, the FEM mesh constitution, the HVSRs computation site, the vertical excitation site and so on are based on the findings obtained from precedence studies (e.g., Hata et al., 2012b). The simulations were conducted both for the stress conditions before the main shock (41 days before the main shock) and for those after the main shock (1.0, 1.3, 1.6, 2.0, 2.5, 3.2, 4.0, 5.0, 6.0, 6.3, 7.9, 8.0, 10, 11, 13, 15, 16, 19, 20, 23, 25, 30, 32, 37, 40, 50, 63, 78, 79, 100, 130, 155, 160, 198, 200, 250, 302, 320, 400, 483, 500, 618, 630, 790, 831, 1000 days after the main shock). Since N-S and E-W components were used as input ground motions in the effective stress analysis, we carried out 2 cases of microtremor simulations. The random excitation was applied in the vertical direction for 327.68 s using a white noise at the ground surface 400 m away from the site for the output of microtremors (located at the top center of the FEM model), as shown in Figure 4. The microtremor H/V spectra were calculated as follows. First, a high-pass filter of 0.1 Hz was applied, and one time section of 163.84 s was extracted from the output time history, which included the center of the time history. Next, Fourier amplitude spectra in the horizontal and vertical directions were calculated with a Parzen window (band width of 0.05 Hz). Finally, a microtremor H/V spectrum was computed. The microtremor H/V spectrum was evaluated in the frequency range from 0.2 Hz to 10 Hz, where the observed microtremor H/V spectra were reliable (see Figure 2).

Figure 6 shows the distribution of the excess pore water pressure ratio based on the effective stress analysis on the day of microtremor measurement (2, 4, 6, 8, 11, 15, 19, 23, 30, 37, 50 and 78 days after the 2011 main shock). The time-dependence of the peak frequency of the simulated microtremor H/V spectra is compared with that observed in Figure 3. Because two cases of simulations were conducted for the N-S and E-W components the mean of the both cases is illustrated. The observed time-dependence of the peak frequency of microtremor H/V spectra was reproduced quite accurately in the simulation, which indicates that the time-dependence of shear modulus was controlled by the generation and dissipation of excess pore water pressure.

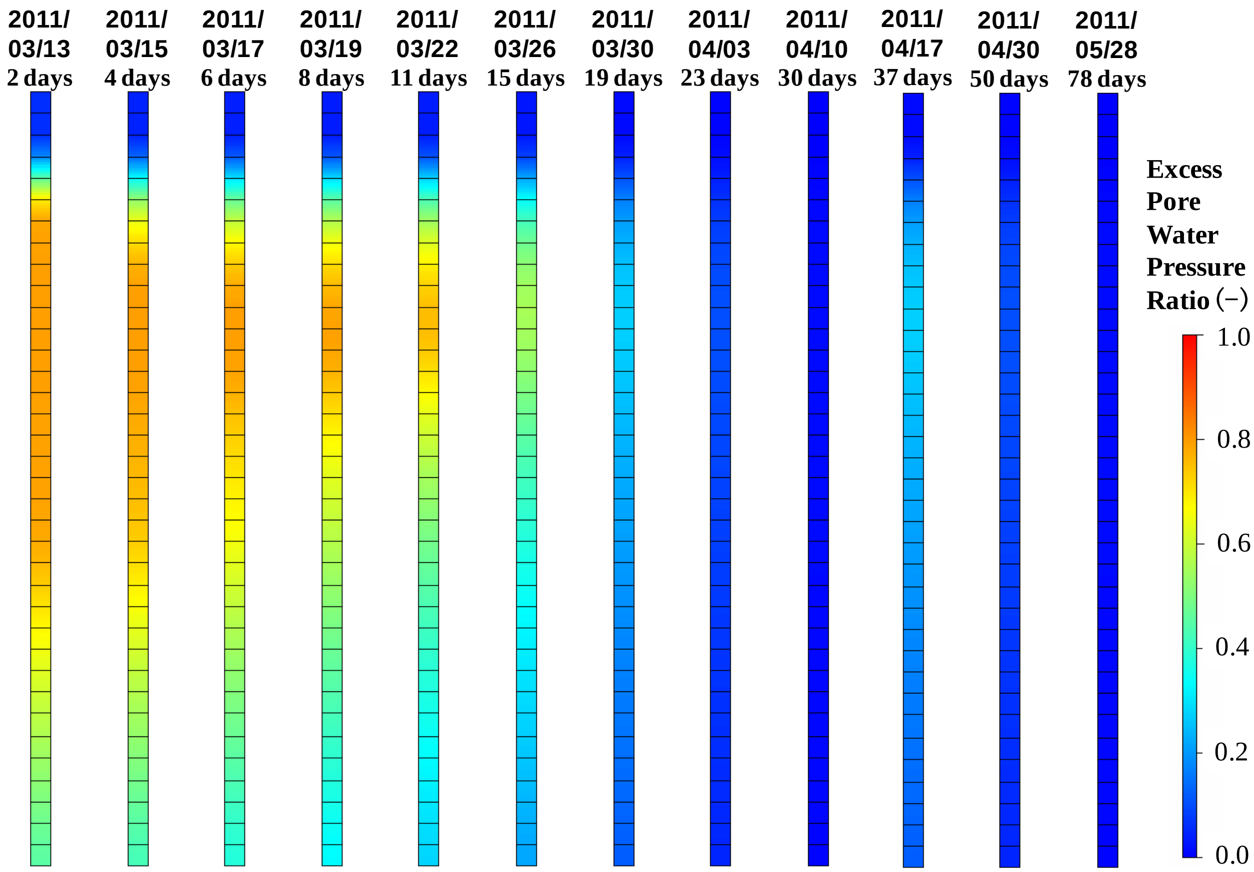

Figure 6. Distribution of excess pore water pressure ratio based on the effective stress analysis

Focused on connection of the results in Figures 3 and 6, effective stress increases with dissipation of pore water pressure, shear modulus is also recovered with increase in confining pressure (effective stress). As a future work, the shape of the H/V spectra based on the microtremor measurements and its simulations should be compared at the same time.

Conclusions

In this study, the recovery process of shear modulus of subsurface soil after the 2011 Tohoku Earthquake sequence at a ground disaster site in Fusa District, Abiko City, Japan, was revealed by intermittent measurements of microtremor for 1,000 days before/after the 2011 main shock. The recovery process was then simulated based on dynamic FEM analyses considering the generation and dissipation of excess pore water pressure with estimated strong motions for the main shock and two large aftershocks. The results of the study can be summarized as follows:

1) The recovery process of the shear modulus of the silty soil was clearly documented in the time-dependent peak frequency of the observed microtremor H/V spectra.

2) The observed time-dependence of the peak frequency of microtremor H/V spectra was reproduced quite accurately in the simulation, which indicates that the time-dependence of shear modulus was controlled by the generation and dissipation of excess pore water pressure.

The above findings suggest the importance of such problem in the prediction/assessment of soil response and related performance of buildings/infrastructures (e.g. earth structures) during strong motion seismic sequences.

Acknowledgments

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