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THE EFFECTS OF SUBSURFACE STRUCTURE ON THE CONCENTRATION OF STRUCTURAL DAMAGE DURING THE 2007 NOTO-HANTO EARTHQUAKE

T. Maeda[1] and R. Shimizu[2]

ABSTRACT

During the 2007 Noto-hanto Earthquake in the central part of Japan, the town of Anamizu experienced severe concentrated damage, where more than 780 Gal was recorded at the K-NET station in horizontal motion. The predominant frequency of the record is about 1.0 Hz, which is widely known as causative of wooden house damages. More than seventy wooden structures were completely destroyed in the area of 500m square; especially high damage ratio was observed in the zone of 100 m square in that area. This distinguished damage concentration can be explained by constructive interference of waves due to subsurface topography. Extensive micro-tremor measurements were carried out to infer subsurface structure by H/V spectra. The predominant frequency at the station was about 1.5 Hz, which may have been lowered from 1.5 Hz to 1.0 Hz by the nonlinear effects of soil layers. The area with completely destroyed houses exhibits predominant frequency between 1.2 Hz and 3.0 Hz. A two-layered subsurface structure model was constructed by simulating H/V spectrum with frequency dependent particle motion of Rayleigh wave fundamental mode. The damage concentrated zone may be located at the mouth of an open-bay-like configuration basin with surface layer of 12 m thick. This subsurface topography was modeled by two-dimensional FEM, and ground motion during the main shock was evaluated as about 10 % larger than that of the K-NET station in terms of acceleration response spectrum around 1 Hz, which is due to constructive interference of reverberation and Rayleigh waves.

Introduction

During the 2007 Noto-Hanto Earthquake, PGA of 782 Gal was observed at the K-NET station in Anamizu town, which was 20 km away from the epicenter. More than seventy wooden structures were completely destroyed in 500 m square at the center of the town. Soft surface soil layer may be attributable for the overall damage; however, there may be some additional reasons for the characteristic damage pattern, namely distinguished damage concentration zone of 100 m square in the area of 500 m square.

[1]Professor, Dept. of Architecture, Waseda University, 3-4-1, Shinjuku-ku, Tokyo, 169-8555, Japan
[2]Ex-graduate student of Waseda University.

Anamizu is a small remote town along the Japan Sea with mostly low-rise structures with few boring data for examination of foundation settlement, and we carried out micro-tremor measurements in 2007 and 2008 for H/V spectra. With these spectra supplemented by a few boring data for design of bridge caissons, the damage concentrated zone is assumed to be located at the mouth of a small bay-like configuration basin. With this insight, subsurface structure enclosed by sloping bedrocks was estimated for the East-West vertical section of damage concentrated zone.

In a rock site away from the town by seven km, the KiK-net station has been operating. It has a vertical array with seismographs at the ground surface and GL-105m; both recorded the main shock and some aftershocks. Temporal observation for aftershocks was carried out by other researchers at the town hall, which is located on hard soil. Utilizing these main shock and aftershock records, bedrock motion in the town during the main shock was estimated. Ground motion in the concentrated damage zone was evaluated by the finite element subsurface model impinged by the bedrock motion, which depicts the constructive wave interference to generate the damage concentration zone.

Distribution of Damage and Predominant Frequency in the Town

The Ratio of Completely Destroyed Structures

The record of the main shock recorded at the K-NET station depicts the predominance of EW component with peaks around 0.7 Hz and 1.0 Hz, as shown in Fig. 1. These frequency contents can be attributable to the heavy damage on low rise wooden structures (Sakai, 2009). Small solid circles in Fig. 2 represent completely destroyed structures, which are almost confined in the area of 500 m square; dense population of these circles is observable in the zone between Anamizu station and the K-NET station. Damage concentration in that zone is quantified by the high ratio of the lot area of completely destroyed structures as is 30 % in a 100 m grid shown in Fig. 2. Examining the aerial photos year by year, the town has been developing almost evenly in the area of 500 m square for more than fifty years, which suggests similar overall quality of the structures in that area.

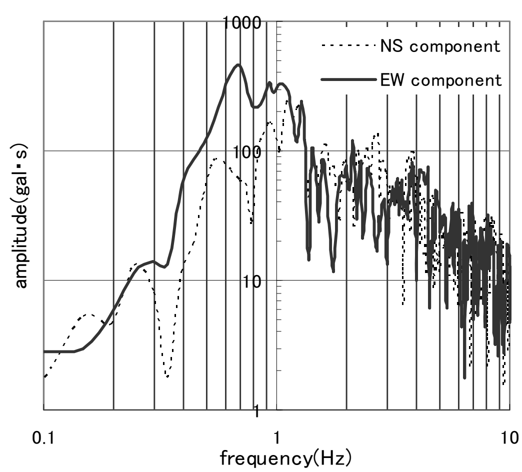


Figure 1. Fourier spectra of the main shock recorded at the K-NET Anamizu station.

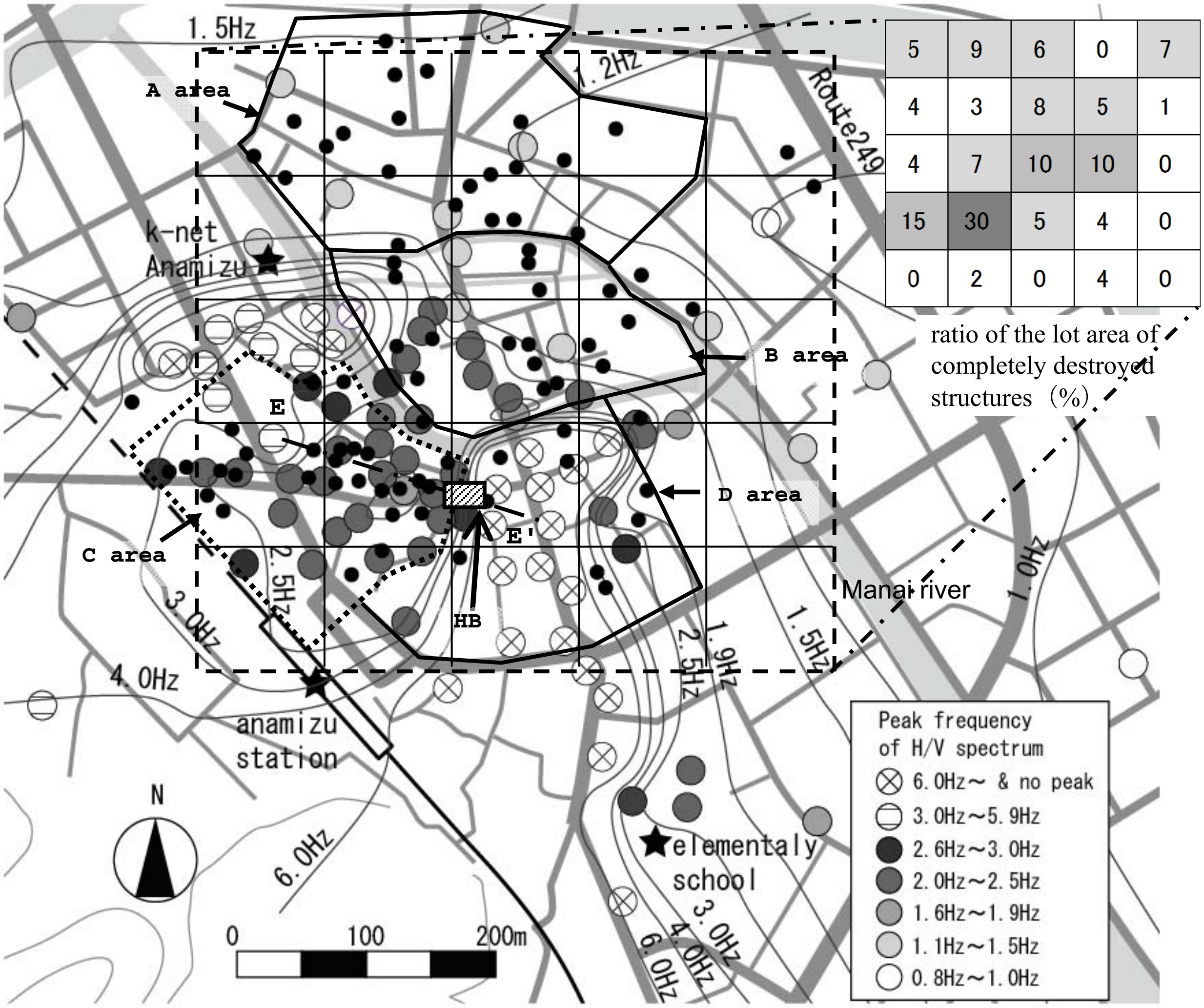


Figure 2. Completely destroyed structures (small solid circle) and peak frequency of H/V spectra of micro-tremor .

In 2007 and 2008, micro-tremor observations at more than fifty points were carried out in the area of 500 m square. Three-component accelerometers up to 100 Hz were used to obtain data of fifteen minutes (Shimizu et al., 2008). Samples of twenty seconds were extracted from these data and used for H/V spectra, an averaged ratio of root mean square of the horizontal amplitudes to the vertical spectral amplitude. The distribution of peak frequencies of the H/V spectra and their contours are shown in Fig. 2. The damage area of 500 m square shows peak frequencies between 1.1 Hz to 3 Hz, and the damage concentrated zone of 100 m square shows about 2 Hz. If we can correlate peak frequency and bedrock depth, the damage concentrated zone may be located at the opening of a small basin toward the north-east.

Estimates of Bedrock Depth

Referring to the PS logging data at the K-NET station, subsurface structure at the damage concentrated zone is modeled by a two-layered model with material property shown in Table 1.

The shear wave velocity of the top layer is an average of the top three layers of the PS logging data at the K-NET station weighted by thickness. The shear wave velocity of the bottom layer is set according to the results of surface wave velocity survey conducted in the high frequency area of H/V spectrum (Inazaki et al., 2009).

Peak frequency [Hz] of H/V ratio of the fundamental Rayleigh mode at the surface can be estimated as 24 divided by the thickness [m] by simulation of the two-layered model. With this relation at hand, layer thickness can be evaluated by peak frequency of the H/V spectrum obtained by micro-tremor measurements. Predominant frequency of 0.8 to 1.5 Hz in the northern area to the river implies thickness of more than 16 m. That of 1.6 to 2.5 Hz in the damage concentrated zone implies thickness of around 12 m, which may be surrounded by shallower bedrock area of 4 to 8 m at the north-west and less than 4 m at the east, corresponding to peak frequency of 3.0 to 5.9 Hz and more than 6 Hz, respectively. It means that bedrock depth changes by about 6m and more than 8 m at the north-west and at the east of the damage concentrated zone.

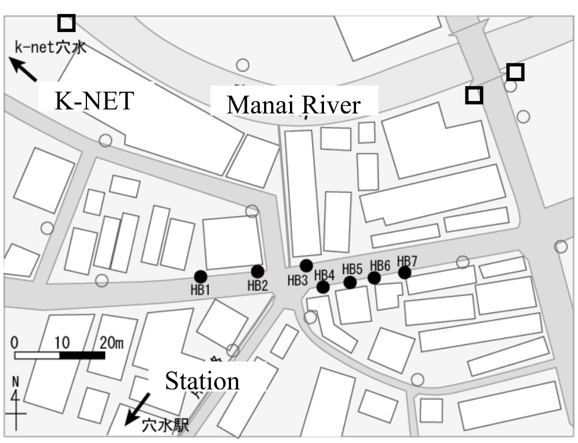
Table 1. Material properties of surface layer and bedrock.

	Vs（m/s）	Vp（m/s）	Density（g/cm^3）
Surface layer	100	710	1.4
Bedrock	500	890	1.8

Subsurface Topography Model

H/V Spectra of Dense Measurements

The damage concentrated zone may be located at the mouth of a small open basin with bay-like configuration, where the predominated EW component during the main shock can be modeled by the P-SV wave filed in the EW section. An anticipated steep slope at the east side of the zone is modeled by simulating EW/V spectral ratio of micro-tremor densely measured with 5 m to 10 m spacing, as shown in Fig. 3. The spectral ratio shows single peak with increasing frequency toward east from 2 Hz to 3.1 Hz and another additional peak emerging at higher frequency around 8 Hz at the east, as shown in Fig. 4. The variation of the peak frequency along the measurement line is summarized in Fig.5.



●: Measurement point for dense observation
○: Measurement point for micro-tremor
□ : Boring site

Figure 3. Measurement points at the east end of the damage concentrated zone.

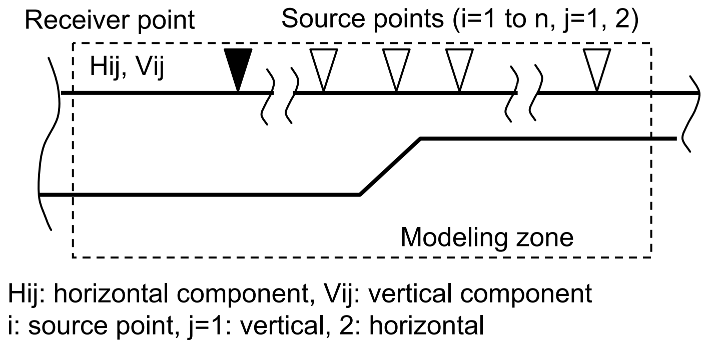


Figure 4. Simulation of H/V spectrum by FEM.

Two Dimensional Simulation of Sloping Bedrock Configuration

EW/V spectra of micro-tremor were simulated by 2D-FEM in P-SV wave field with horizontal and vertical point excitations on the surface, according to Eq. 1 and Fig. 4 (Wakamatsu and Yasui, 1995). Steady-state vibration analysis up to 10 Hz was carried out with frequency increment of 0.1 Hz; the FEM model has horizontal extent of 250 m and vertical depth of 139 m with energy transmitting boundary equipped at the periphery and viscous boundary at the bottom. Hysteretic material damping of 2 % is assumed for layers.

$$EW/V = \sqrt{\sum_{i=1}^{n}\sum_{j=1}^{2} H_{ij}^{2}} \Bigg/ \sqrt{\sum_{i=1}^{n}\sum_{j=1}^{2} V_{ij}^{2}} \tag{1}$$

According to peak frequencies of H/V spectra, bedrock depth was evaluated as 14 m and 3 m across the edge of the damage concentration zone, i.e. 11 m difference across the anticipated sloping bedrock. HB5 in Fig. 3 is assumed as the center of the bedrock slope and the four models with different slope angles shown in Table 2 were studied. Peak frequency of the simulated H/V spectrum is summarized in Fig. 5. The model D with slope angle of 37 degrees shows relatively better fit of the peak frequencies, with the simulated H/V spectra as shown in Fig. 6, which is used in the following analyses.

Table 2. Bedrock slope models.

Model	Slope angle (deg.)	Horizontal projection (m)
A	90	0
B	63	6
C	45	11
D	37	15
E	27	22

Evaluation of the Ground Motion during the Main Shock

Bedrock Motion

The KiK-net Anamizu station is located at the east of the town center by about 6 km with a vertical array of seismographs at GL and GL-105 m in rock site. The main shock was recorded

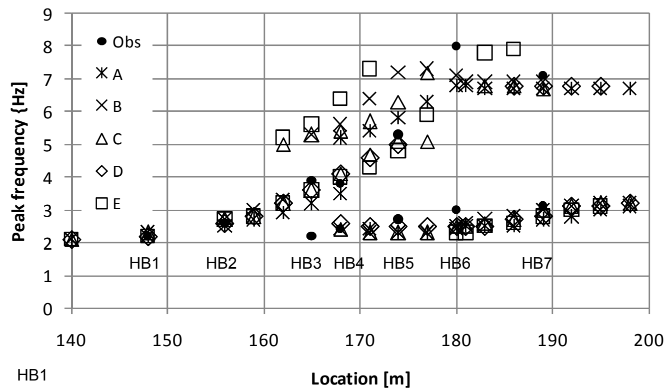
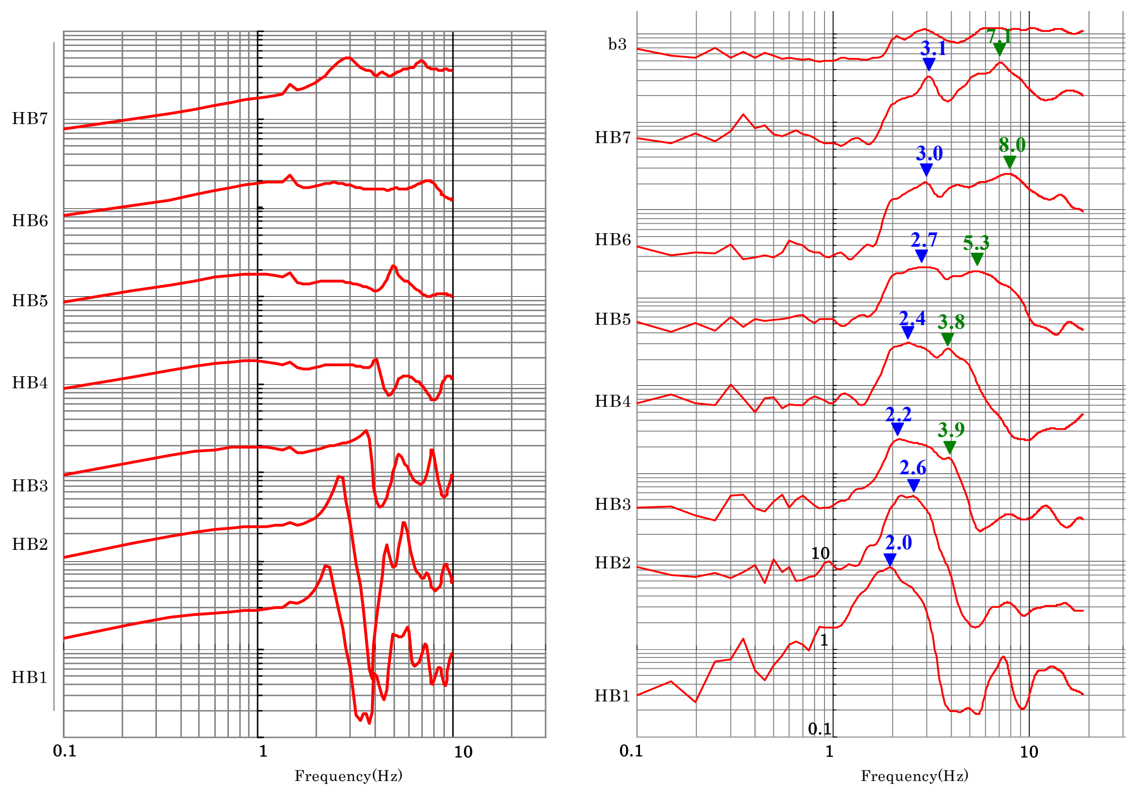


Figure 5. Variation of peak frequencies of H/V spectrum along E-E'.



(a) Micro-tremor measurements

(b) FEM simulation (Model D)

Figure 6. H/V spectrum along E-E'.

at the station for about 9 seconds from the onset as shown in Fig. 7. Spectral ratio of EW component at the surface to GL -105 m shows little amplification below 2 Hz in Fig. 8 (a) and the subsurface structure of upper 105 m may have scarcely affected the bedrock motion during the main shock.

Temporary observation of aftershocks was carried out at the town hall, a hard soil site, which is located 1 km east of the K-NET station (Yoshimi and Yoshida, 2008). Spectral ratio of the aftershock records to that observed at the KiK-net station is shown in Fig. 8(b), which depicts

3 to 4 times of amplification around 1 Hz. Concentrating on around 1 Hz and utilizing these examinations, the record at GL -105 m was scaled by three times to estimate bedrock motion beneath Anamizu town.

Material Non-linearity in Surface Layer

During the main shock, surface layers must have experienced large strain and behaved non-linearly at the K-NET station (Iwata et al., 2008). Subsurface structure at the station was simplified by three-layers as shown in Table 3; the top layer of Vs 100 m/s and the second layer of 300 m/s are the compiled results of PS logging profile at the K-NET station, and the bedrock of Vs 500 m/s comes from the surface wave survey as before (Inazaki et al., 2009). Dependence of rigidity on shear strain was deduced based on the assumption of one-dimensional wave propagation (Tokimatsu et al., 1989); relation between estimated effective shear strain by the main shock velocity record and estimated predominant frequency of the surface layer was utilized to plot Fig. 9(a). Dependence of damping ratio on shear strain was referred to the typical laboratory test on silt. The second layer and the bedrock were assumed to remain elastic. Fig. 9(b) shows the estimated motion by the equivalent linear approach, which compares the observed data low pass filtered at 2.5 Hz relatively well. The effective shear strain of the surface layer is about 1 %.

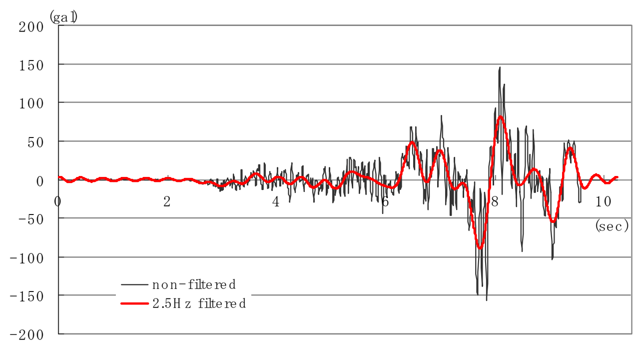
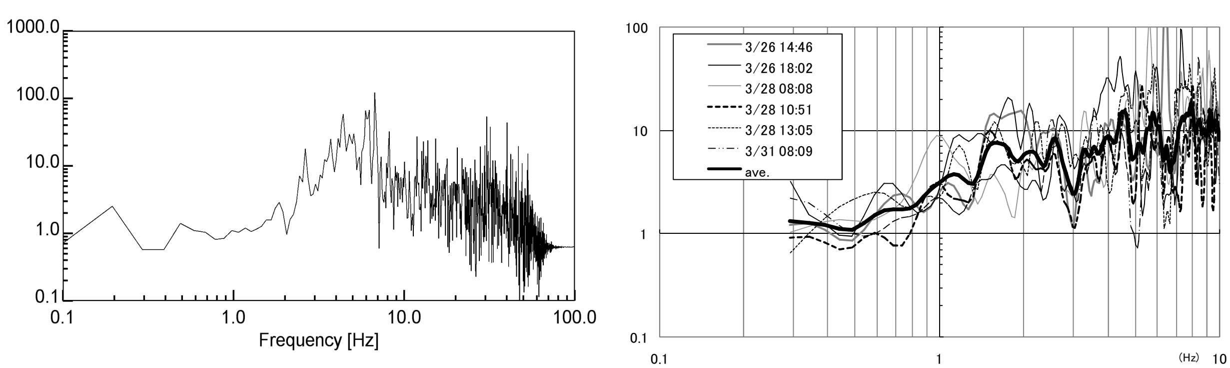


Figure 7. EW component of acceleration recorded at GL -105 m of KiK-net Anamizu.



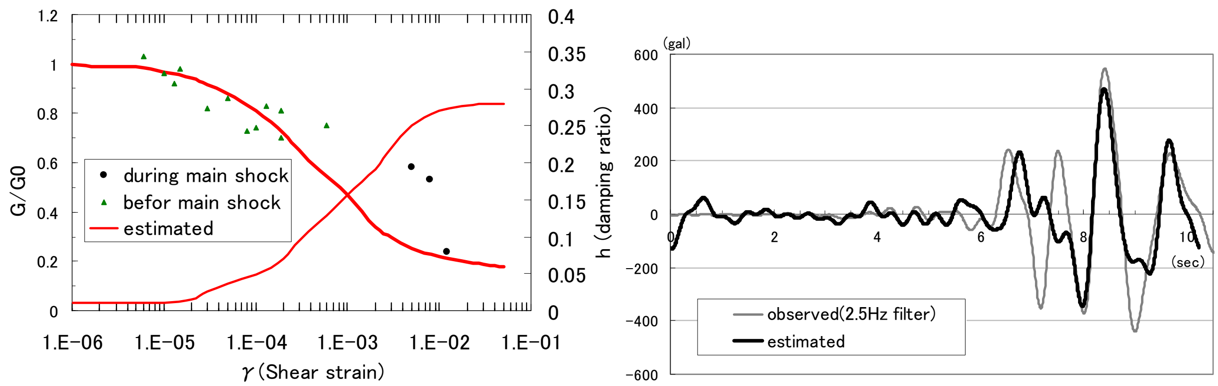
(a) GL to GL -105 m at KiK-net

(b) Town hall to GL -105 m of KiK-net

Figure 8. Spectral ratio of EW component.

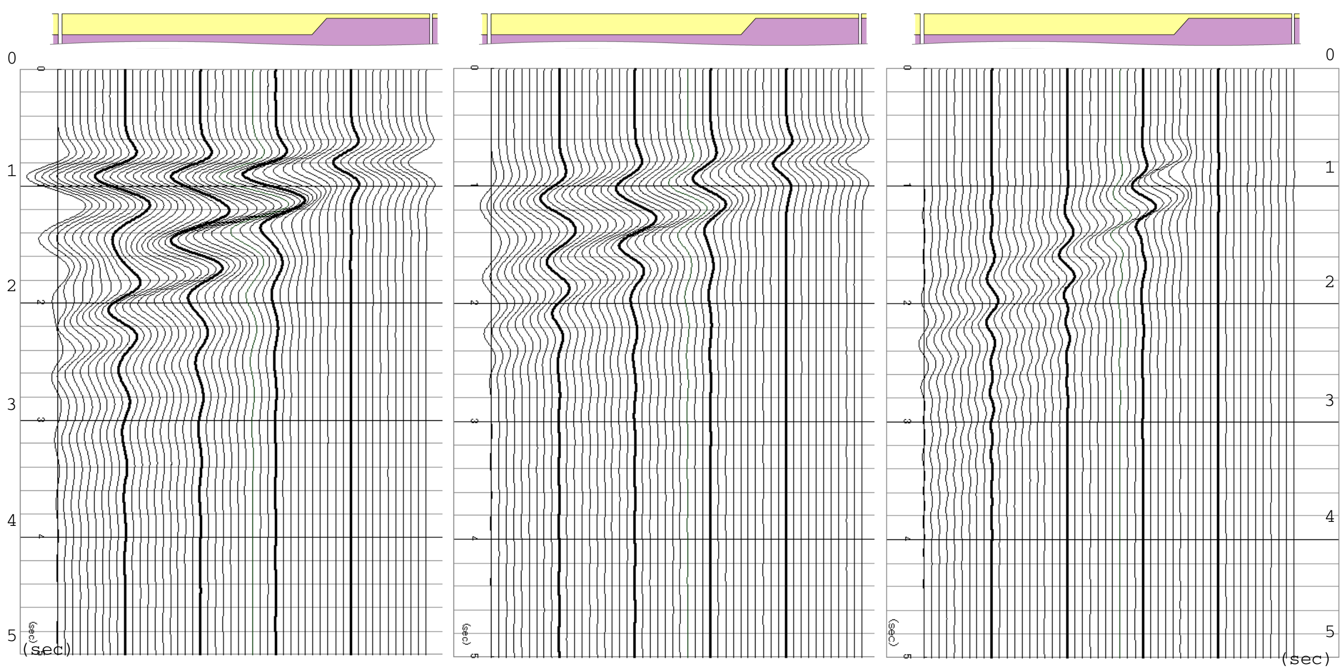
Table 3. Sub surface model for the K-NET station.

	Thickness (m)	Vs(m/s)	Vp(m/s)	Density (g/cm^3)
Top layer	14	100	710	1.4
Second layer	21	300	890	1.8
Bedrock	—	500	890	1.8



(a) Strain dependence of surface layer (b) Simulated waveform

Figure 9. Simulation of the main shock record at K-NET Anamizu.



(a) Horizontal component (b) Horizontal component (with reflection layer) (c) Vertical component

Figure 10. Acceleration waveforms for the east slope model with Ricker wavelet input.

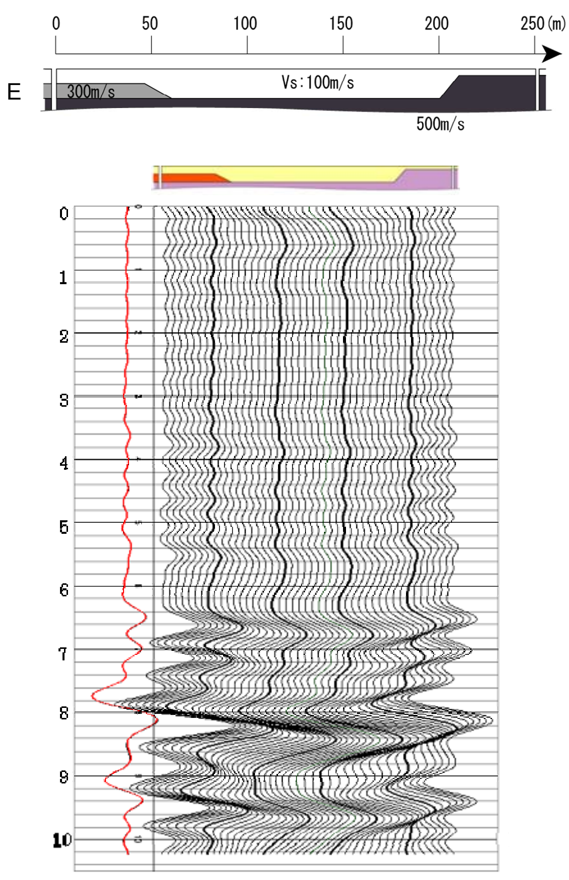
Evaluated Ground Motion

The surface layer is assumed to be confined by sloping bedrock at both sides with slope angles of 37 degrees. Basic characteristics of wave propagation were studied by impinging

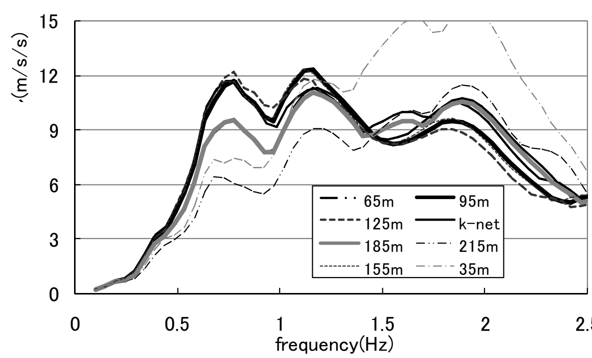
Ricker wavelet of center frequency of 2 Hz. Fig. 10 (a) and (c) show waveforms of horizontal and vertical ground motion. Fig. 10 (b) shows horizontally traveling waves extracted from (a) by installing reflecting layer beneath horizontal layers. Comparison of these figures reveals that the wave fields are composed of reverberation in the horizontal layers and horizontally traveling waves; the latter is estimated as Rayleigh wave fundamental mode by examining phase velocity and particle motion.

Ground motion along E-E’ section in Fig. 2 of the damage concentrated zone was estimated by impinging the evaluated bedrock motion to the two-dimensional equivalent linear FEM model. Installing similar slope structure at the west side, ground motion was evaluated in the basin as shown in Fig. 11(a), where constructive wave interference similar to Fig. 10 is observable. Fig. 11(b) shows acceleration response spectra of the ground motion; which depicts predominant peaks around 0.7 Hz and 1.0 Hz. The ratio of these response spectra to that simulated at the K-NET station in Fig. 11(c) reveals about 10 % increase of spectra interior of the basin at 95 m, 125m, and 155m, around 1.0 Hz.

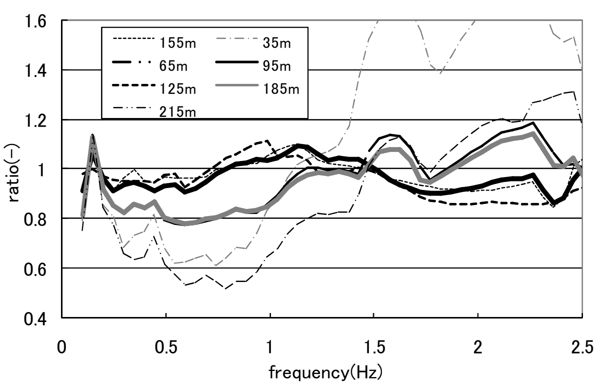
It is not easy to prove that 10 % increase of the input is attributable to the generation of damage concentrated zone; however, taking the three-dimensional contribution of wave interference due to bay-like configuration into account, topographical effects of subsurface structure must be the main cause of the damage concentration.



(a) Acceleration waveform



(b) Acceleration response spectra



(c) Response spectrum ratio

Figure 11. Simulated ground motion by equivalent linear analysis and acceleration response spectra and its ratio to simulated response at K-NET Anamizu.

Conclusions

Generation of damage concentrated zone of 100 m square observed for the town of Anamizu during the 2007 Noto-hanto Earthquake is explained by the subsurface topography effects. These effects are simulated by two-dimensional FEM subsurface model with estimated bedrock motion during the main shock. The model was constructed by simulating densely measured H/V spectra of micro-tremor. The bedrock motion was estimated by scaling the rock site record of the main shock with consideration on spectral ratio of aftershock records between the hard soil site and the rock site. That bedrock motion was justified by the simulation of the main shock record at the soft soil site by equivalent linear approach with strain dependence evaluated by the main shock velocity record.

FEM simulation shows that the constructive wave interference in the horizontal layers confined by sloping bedrocks is attributable to the 10 % increase of acceleration response spectrum around 1 Hz at the location corresponding to the damage concentration zone. It is not easy to prove that 10 % increase of the input is attributable to the generation of damage concentrated zone; however, taking the three-dimensional contribution of wave interference due to bay-like configuration into account, topographical effects of subsurface structure must be the main cause of the damage concentration.

Acknowledgments

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