Site Specific Ground Motion Amplification Study in Sendai Basin for Seismic Design Based on Observation Records During the 2011 Tohoku Earthquake

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SUMMARY:
Ground motion spectral characteristics have been studied based on observed strong motion records in relation an existing geological structure. Ground motion characteristics in Sendai city, Japan during the 2011 Off Pacific Coast Tohoku Earthquake (M9.0) show strong site effect due to geological condition, not only surface geology but also deep underground structure. Obtained research results and lessons from the huge event discussed for seismic design of building structures and other earthquake counter measure applications from the point of seismic micro zoning.

Keywords: the 2011 Tohoku Earthquake, ground motion amplification, seismic design, seismic micro zoning

1. INTRODUCTION

The 2011 Off Pacific Coast Tohoku Earthquake (M9.0) occurred on March 11, 2011 in north-eastern Japan and caused tremendous damage. Source process with large rupture distribution is on the fault plane of dimension 450 km length by 150 km width, as shown in Figure.1.1 (Japan Meteorological Agency, 2011). Ground motion characteristics during severe shaking have shown variable characteristics depending on influence from seismic source, wave propagation path and local site geology. The ground motion characteristics in local site play an important role into structural damage features. In Sendai, observed ground motion characteristics during the 2011 Tohoku Earthquake and its influence on structural damage characteristics were confirmed focusing on site specific ground motion characteristics (Motosaka, 2012).

Consideration of site specific ground motion is very important in seismic design of building structure, since the city is located on geological structure which consists of irregularity from deep underground to subsurface including lateral inhomogeneity of local soils.

This paper first describes the site specific ground motion amplification characteristics in Sendai during the 2011 Tohoku earthquake, discussing in relation seismic design spectra and geological model. Second, a specific site is investigated using historical strong motion records in hilly zone Aobayama, where structural damages occurred to the 8- 9- story buildings (Tsamba and Motosaka 2011). Azimuth dependent ground motion characteristics are also addressed comparing as engineering bedrock motion for the earthquakes.

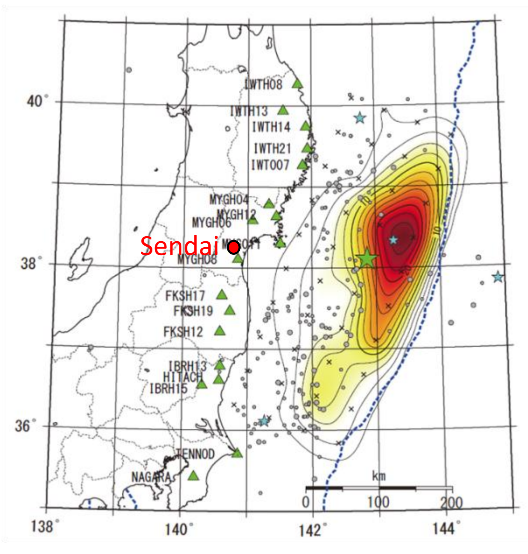

Figure 1.1. Slip distribution on the fault (after JMA)

2. GEOLOGICAL ENVIRONMENT AND STRONG MOTION RECORDS

2.1. Geological Structure in Sendai area

Geological map of the Sendai area (Japan Geological Survey, 2010) is shown in Figure.2.1(a) together with strong motion sites in the city. The Nagamachi-Rifu fault is an active reverse fault which trends NE-SW across the central part of Sendai City for over 21 km distance and the fault does not emerge at the surface (Sato et all, 2002). South east side of the fault is alluvial plain; north-west side is diluvium terrace surrounded by hilly zone to the west; north part of the city is soft soil layer deposit on the hard rock. Quaternary layer bottom is shown in Figure.2.1(b). Deep underground structure is described in the later section (ref. to Figure 4.1).

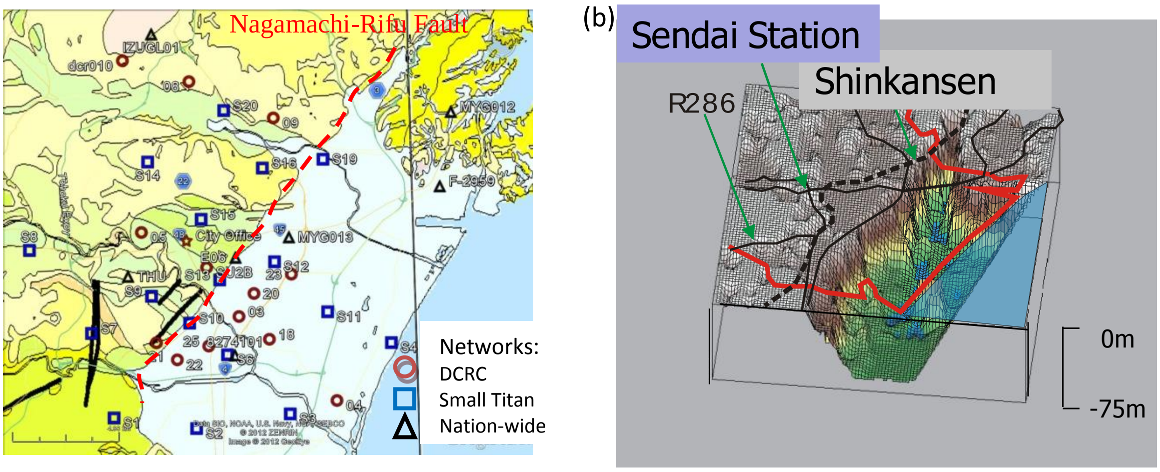

Figure 2.1. (a) Geological map and site locations of strong-motion networks
(b) Quaternary layer bottom

2.2. Overview of Strong Motion Records

Strong motion records were obtained during the 2011 Tohoku Earthquake in Sendai city, from nation-wide seismic networks, namely K-NET from NIED, Japan Meteorological Agency (JMA) and Building Research Institute (BRI). Local networks are also observed records, Disaster Control Research Center of Tohoku University (DCRC) (Ohno and Motosaka, 2011) and Small Titan network of Tohoku Institute of Technology (TOHTECH) (Kamiyama et al, 2012). In the city, range of PGA values are from 215 cm/s/s to 1853 cm/s/s and that of PGV values are from 27 cm/s/s to 108 cm/s.

3. COMPARISON OF RESPONSE SPECTRA AND DESIGN SPECTRA

3.1. Seismic Design Codes for Buildings in Japan

The basic concept for seismic design spectra of earthquake motion in verification procedures is (1) basic design spectra defined at engineering bedrock (2) evaluation of surface soil amplification factor (Kuramoto, 2006). Two limit states should be considered for building structures to protect the life and property of occupants against earthquake motion: (1) Safety Limit and (2) Damage Limit. Design ground motion used for seismic design at the Life-Safety limit is the site-specific ground motion of an extremely rare earthquake expected to occur once in approximately 500 years. Engineering bedrock is a soil layer with shear wave velocity (V_S) of 400 m/s or more. Design earthquake acceleration spectra $S_0(T)$ at engineering bedrock with 5% damping factor is defined by Eqn.3.1. Damage Limit state should be reduced to one fifth of that for safety limit.

$$S_0(T) = (3.2 + 30T) \qquad T < 0.16$$
$$S_0(T) = 8.0 \qquad 0.16 \le T < 0.64 \qquad (3.1)$$
$$S_0(T) = \frac{5.12}{T} \qquad 0.64 \le T$$

Design response spectra at ground surface with 5% damping factor is defined $S_A(T)$ in Eqn.3.2.

$$S_A(T) = G_S(T) \cdot Z \cdot S_0(T) \qquad (3.2)$$

where, $G_S(T)$: surface soil amplification factor and Z: seismic zone factor (0.7 – 1.0).

3.2. Surface Soil Amplification Factor in Sendai City

Surface soil amplification factor is estimated in Sendai city along a line perpendicular to Nagamachi-Rifu fault from Sendai City office on diluvium terrace to Arahama Elementary School on alluvial deposit as shown in Figure 3.1.(a) together with the geological structure in Figure 3.1.(b).

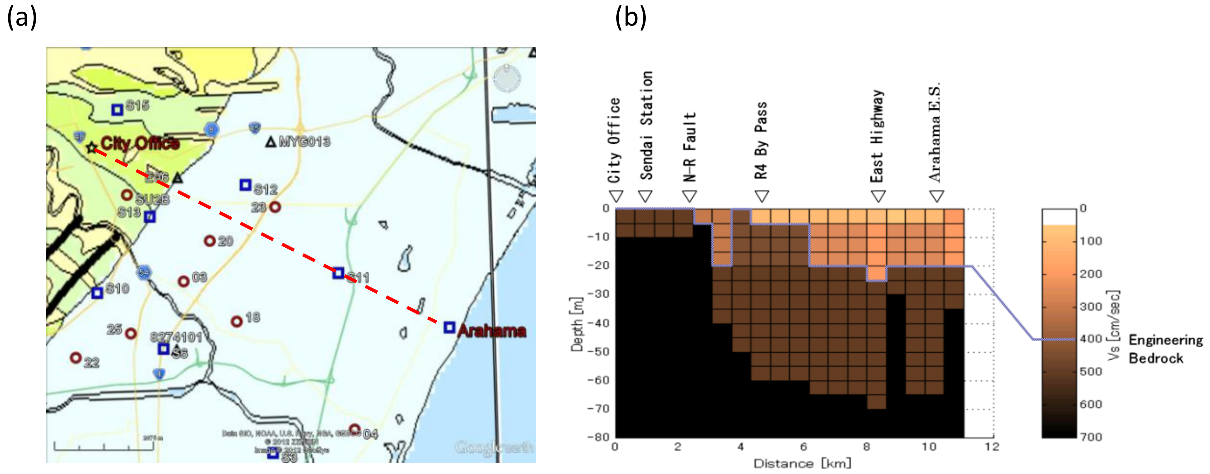

Figure 3.1. (a) Sendai City office and Arahama Elementary School Line (b) Section of Layers

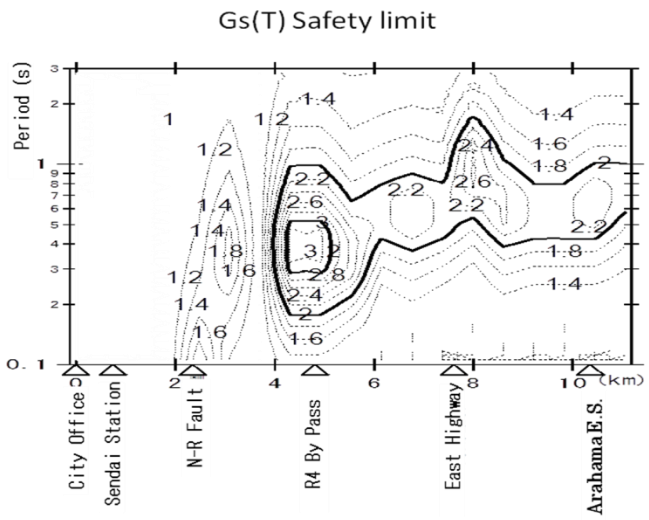

Figure 3.2. Surface Soil Amplification Factors Gs(T) for Safety Limit Along the Line

Figure 3.2 shows the soil amplification factor *Gs*(*T*) calculated for safety limit of design spectra based on surface geology along the line.

The results are as follows. (1) In the center of the city, the surface soil amplification factor is unit. (2) In Nagamachi Rifu fault area, 0.6 sec period amplifies 1.4 times and around 1 sec period is amplifies 1.2 times. (3) In Oroshimachi area (Route4 by Pass), the largest amplification factor is 3 in period 0.4; another short period ranges of 0.6 sec is 2.4 times and 0.8 sec is 2.2 times, respectively. (4) In the Arahama area, amplification factor is 2 for 1 sec period range. The surface soil amplification factors will be discussed comparing with observed spectral amplification in later section.

3.3. Comparison of observed response spectra

During 2011 Tohoku earthquake, observed response spectra within Sendai basin structure are compared with design spectrum of Safety limit of Japanese Building Code. It should be noted that SU2B site is recognized as engineering bedrock site in Sendai city. Although quite different ground motion amplification characteristics are recognised based on PGA values and response spectra of the observation sites in the basin, it can be seen similar characteristics in small zone based on existing deep underground structure and subsurface structure information. Regarding design spectra issue, surface geology is also important. Therefore, for the purpose of seismic micro zoning, site effects as spectral amplification are also investigated for the following divided five zone parts considering the site profile from the model. In each zone, spectral values at around 1 sec, short period range and long period range were discussed.

3.3.1.Central part: Zone-1

Central part of city is included JR Sendai station and downtown area on diluvium terrace. PGA value is range 318 cm/s/s ~ 521 cm/s/s. Comparison of the site SU2B response spectra with design spectra, it is shown that 0.4 sec; 1.2 sec and 3.0 sec period is slight larger. Other sites in the fault area are amplified about 1.5 times at short period range; also 3 sec long period is larger.

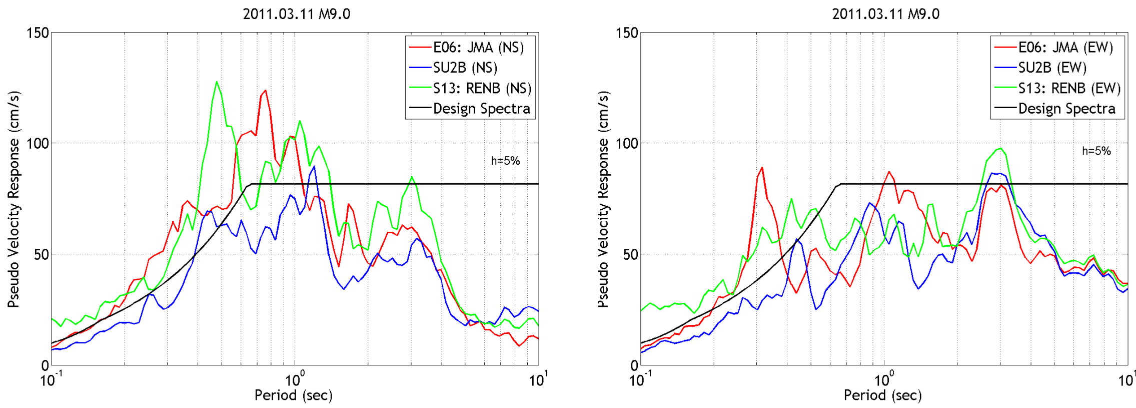

Figure 3.3. Pseudo-Velocity Response Spectra at the sites in central part

3.3.2. East part: Zone-2

The east part is alluvial deposits. PGA is 500 ~ 600 cm/s. Sites dcr023 and SIKO are located in Oroshimachi area and those are large amplification 1.5 to 2 times than design spectra in short period 0.6 sec ~ 0.8 sec. Sites dcr004 and ARAH are located along coast line and around 1 sec period is 2 times amplified dominantly in NS component.

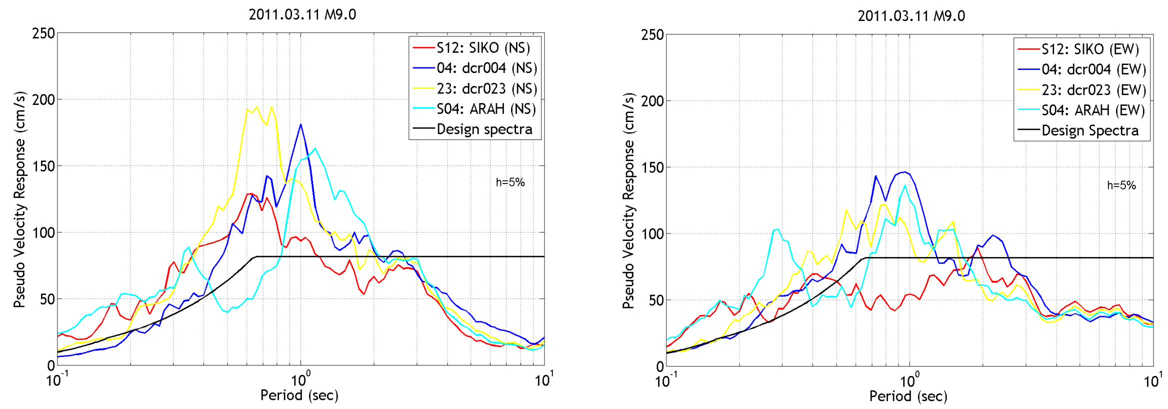

Figure 3.4. Pseudo-Velocity Response Spectra at the sites in east part

3.3.3. North part: Zone-3

North part of city is Izumi area. This zone has contrast geological structure where alluvial layers deposit on rock. PGA is about 700 ~ 800 cm/s/s. It is recognized that the sites dcr008 and dcr009 are shown amplification 2 ~ 3 times in short period range 0.4 sec and 0.7 sec.

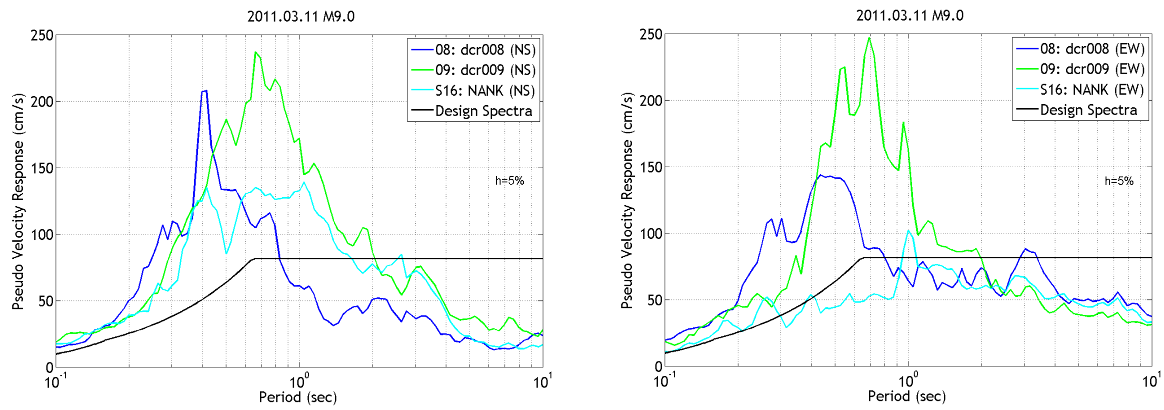

Figure 3.5. Pseudo-Velocity Response Spectra at the sites in north part

3.3.4. South part: Zone-4

South part is Nagamachi area. The bed rock depth of this area is deep. The south-east of the Nagamachi-Rifu fault is alluvial deposit. PGA is 600~700 cm/s/s in centre part (dcr025,HNAG); others are 300~500 cm/s/s. NS component, 1 sec period amplification is sharp in at 3 sites, 2~4 times larger; 3 sec period amplification is cover all sites, 2~2.5 times larger, respectively comparing design level.

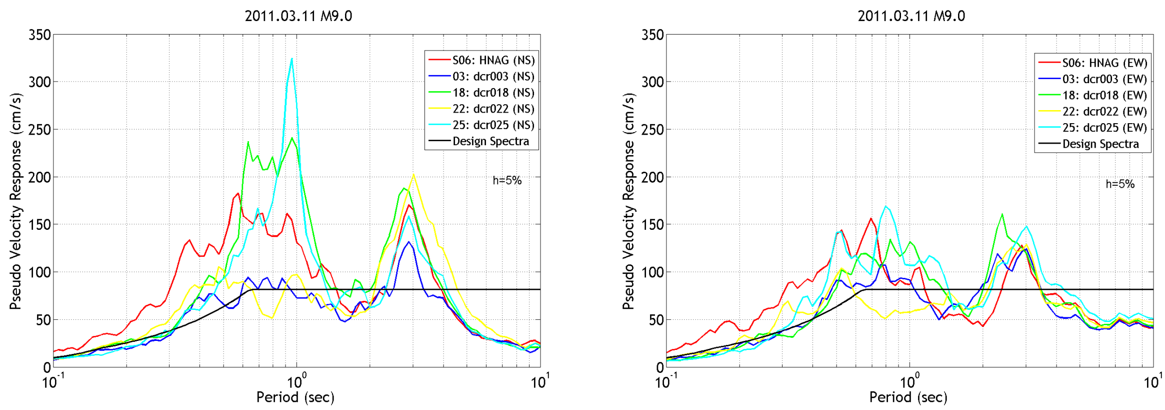

Figure 3.6. Pseudo-Velocity Response Spectra at the sites in south part

3.3.5. West part: Zone-5

West part of city is covering hilly zone area. PGA is 333~471 cm/s/s. In this area topographically irregular, site amplification in 1 sec at sites THU and TITK are 2~3 times in NS comp, while 3 sec period is amplified 1.5 times in EW comp. Long period 4 sec is slight larger in NS comp. than design spectra. Site dcr.005 is located on the foot of hill. The site amplifications at THU will discuss in later.

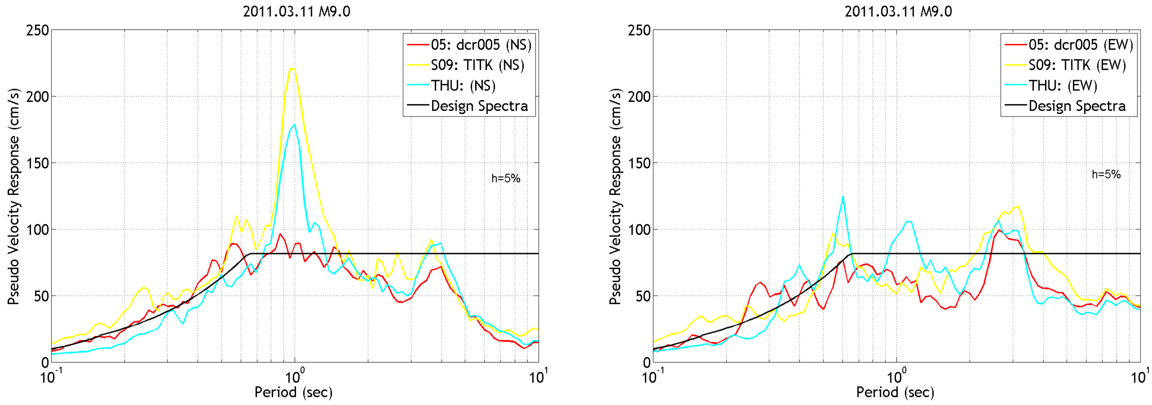

Figure 3.7. Pseudo-Velocity Response Spectra at the sites in west part

The observed amplification factors in Zone-1 and Zone-2 are almost consistent with corresponding value of those estimated surface soil amplification factor.

4. COMPARISON OF DOMINANT PERIODS OF OBSERVED MOTIONS AND THEORETICAL DOMINANT PERIOD OF DEEP UNDERGROUND STRUCTURE

4.1. Theoretical Dominant Period of Deep Underground Structure

Figure 4.1 shows bedrock depth and dominant period map based on the deep underground structure (Miyagi Prefecture, 2005). The geological structure is determined based on many kinds of geophysical information which concludes gravity anomaly data, hot-spring borehole data, reflection survey data, microtremor measurement data and geological literature information. Deep underground geological structure has modelled within 250 meter mesh database. It is noted that bedrock depth is shallow in north-east part; the depth increases toward west. Corresponding dominant period for vertical incident S-wave becomes longer toward west while eastern part is about 1 sec; the central part is about 2.5 sec; western part is about 3 sec (Motosaka et al, 2006).

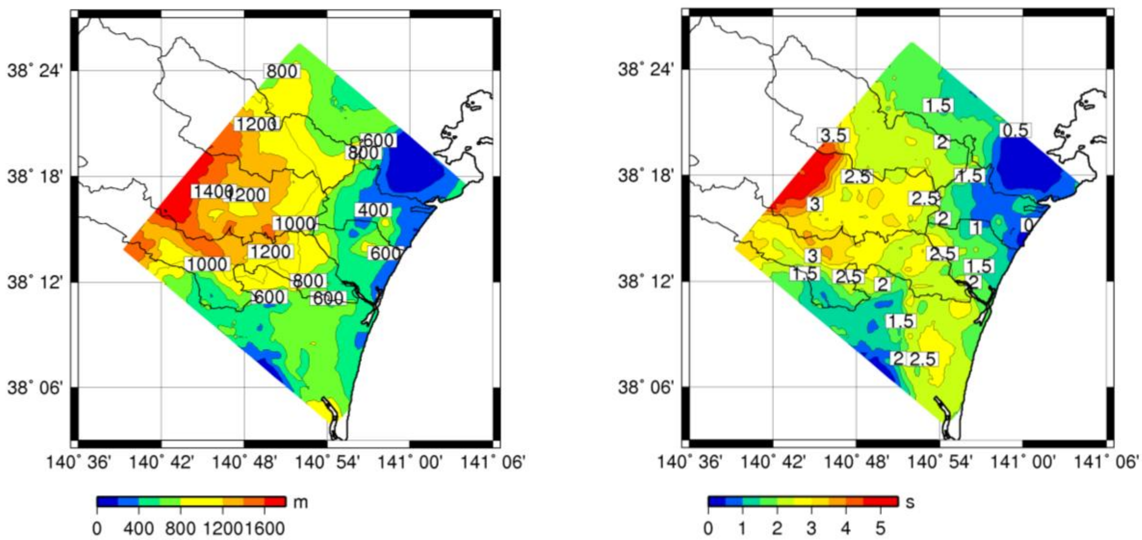

Figure 4.1. Deep Underground Structure in Sendai Area (a) Bed rock depth, (b) 1st Dominant period for vertical S-wave incidence

4.2. Comparison of Observed and Theoretical Dominant Period

Observed strong motion records during the 2011 Tohoku Earthquake is compared versus the model as real-event, which shows long period contents of spectral ranges. Strong motion network map shows intersection of structure donated by lines, Line-A, Line-B and Line-C. DCRC network sites are used along each section and long period dominant periods based on the observed records are plotted and compared with theoretical calculated fundamental period for vertical S-wave incidence. The symbol '□' shows dominant period of NS component and the symbol '○' EW component. The results are follows. 1) Along Line-A, perpendicular direction to the fault, spectral distribution is large range from short period to long period. 2) Along Line-B, parallel direction to the fault, long period dominance of 3 sec is recognized around Nagamachi area, which is almost the same as the theoretical dominant period. 3) Along Line-C, line from east to west, dominant period changes drastically and the dominant periods' difference the 2 sites, 1.8 sec and 4 sec (Figure.4.2.)
The trend of the observed long period change of the spectra is consistent with that of calculated values, but a bit longer at some period range. The dominant periods of 3 sec at around Nagamachi area are almost the same as the theoretical dominant period. 4 sec in west area is larger than calculated. It is noted that the dominant period of NS component and EW component are different at some observation sites.

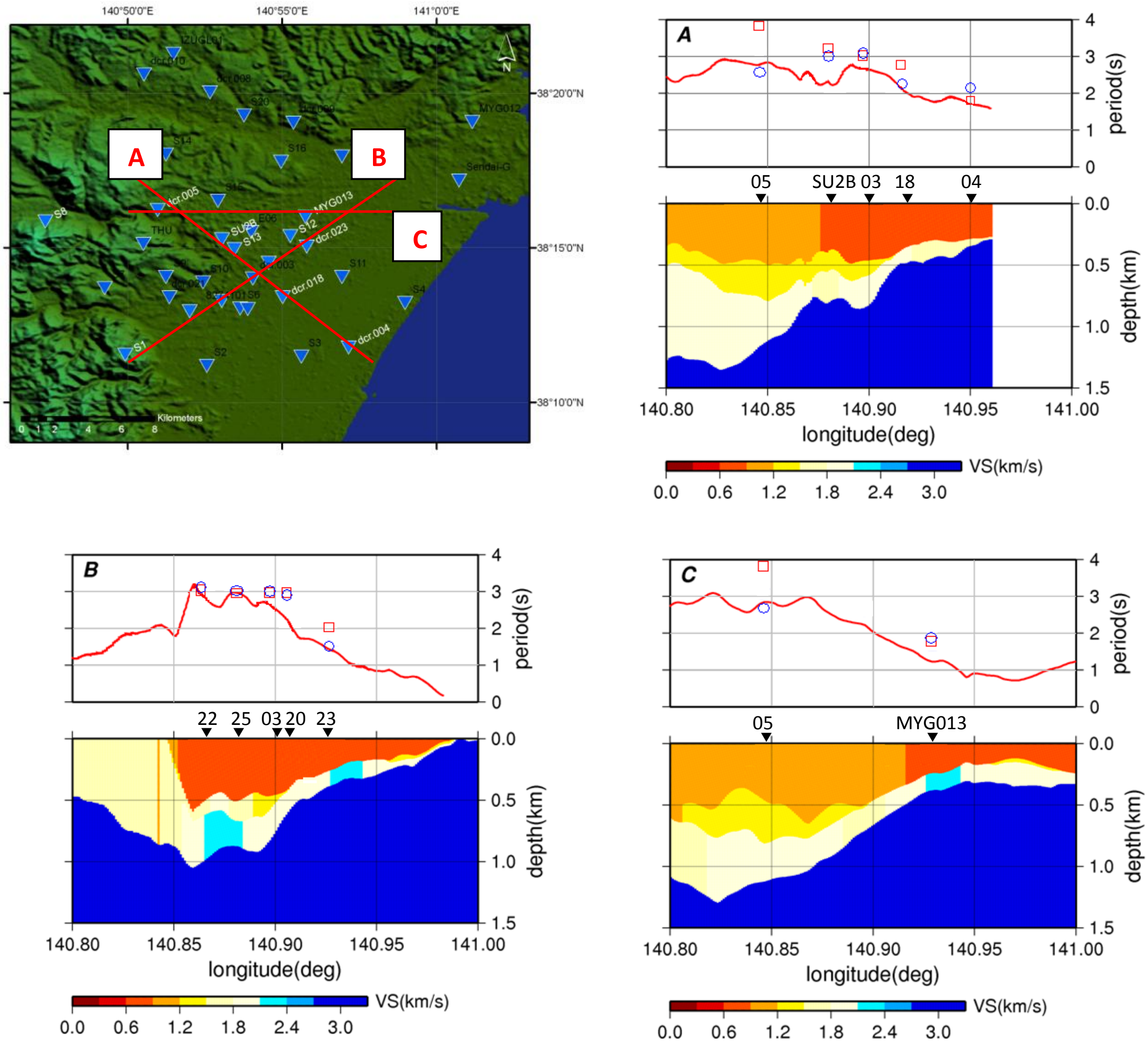

Figure 4.2. Comparison for observed fundamental period and theoretical model

5. HISTORY OF STRONG MOTION RECORDS IN AOBAYAMA

5.1. Strong Motion History

In the Aobayama campus of Tohoku University, where 8- 9- story reinforced concrete buildings were damaged during the 2011 Tohoku earthquake, therefore it is investigated the ground motion amplification on the hill (Tsamba and Motosaka, 2012). Strong motion records since 1978 were used to investigate site amplification characteristics in taking account structural damages during past disastrous earthquakes. The 1978 Miyagi-ken Oki earthquake (M7.2) caused destructive damage to buildings in Sendai and at Aobayama of hill the fundamental natural period was confirmed 0.8 sec from analytical and obtained records (Shiga et al., 1979). The 1998 Miyagi Nanbu earthquake (M5.2), shallow inland earthquake occurred within epicentral distance 7 km and PGA value is 435 cm/s/s in EW direction, near source ground motion characteristics with 0.3 sec period caused structural damages to low story buildings were confirmed (Motosaka, 1998). Strong motion records at sites used to investigate spectral amplification characteristics discussing the azimuth dependency of ground motion propagation through basin structure from seismic source areas.

5.2. Spectral Amplification Characteristics

5.2.1.Miyagi-ken Offshore earthquakes

Observed strong motion records at the sites during 1978 Miyagi-ken Oki earthquake (M7.2) and 2011 Off Pacific Coast Tohoku Earthquake (M9.0) showed in Figure 5.1 and peak ground accelerations are 258 cm/s/s and 333 cm/s/s for Aobayama; 251 cm/s/s and 318 cm/s/s for Sumitomo, respectively. The 2011 Tohoku earthquake waveform comprises two main phases and further spectral investigation is done at each phase separately. Although the peak ground accelerations at two sites are almost same level, the ground motion characteristics are different at some specific spectral range.

The spectral amplification features are as follows in Figure 5.2. (1) The two phases of the 2011 Tohoku earthquake show quite different spectral amplification. (2) As for the 1st phase, the spectral amplification at around 1 sec is recognized only in EW component. NS component is not amplified at around 1 sec. The dominant period is recognized at 2.5 sec in EW component. But the amplification in hill is not significant. (3) As for the 2nd phase, NS component is strongly amplified around 1 sec period which is strongly related to the structural damage of THU building. The spectral amplification by 2 times at 4 sec is also recognized in NS component. The spectral dominance at 3 sec is recognized in EW component but amplification is small. (4) The spectral values of 1978 Miyagi-ken Oki earthquake at around 1sec period content are larger in the NS direction and the spectral amplification in the hill is about two times, which is similar to the 2nd phase of the 2011 Tohoku earthquake. The longer period contents are about half compared to that of 2nd phase. (5) The 2005 Miyagi-ken Oki earthquake (M7.2), spectral amplifications are commonly larger in 1 sec period dominantly in NS direction and spectral range about 3 sec is appeared.

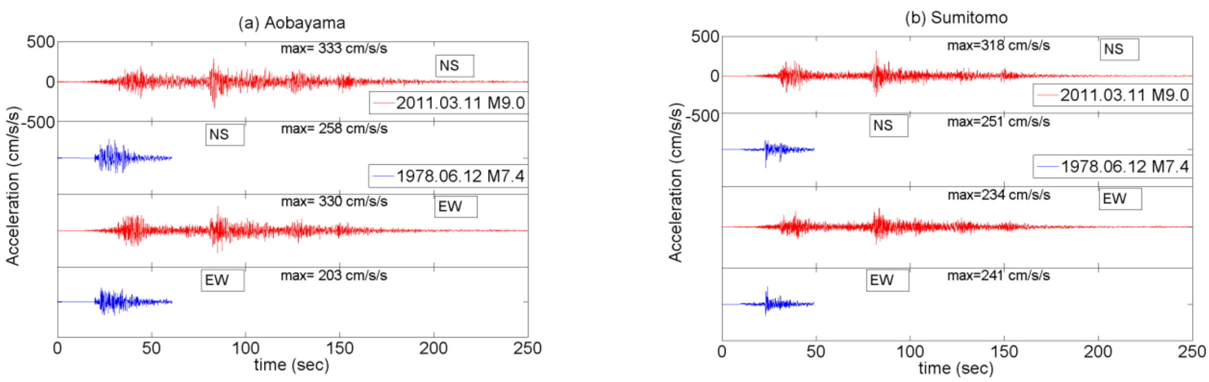

Figure 5.1. Observed acceleration waveform (a) Aobayama and (b) Sumitomo

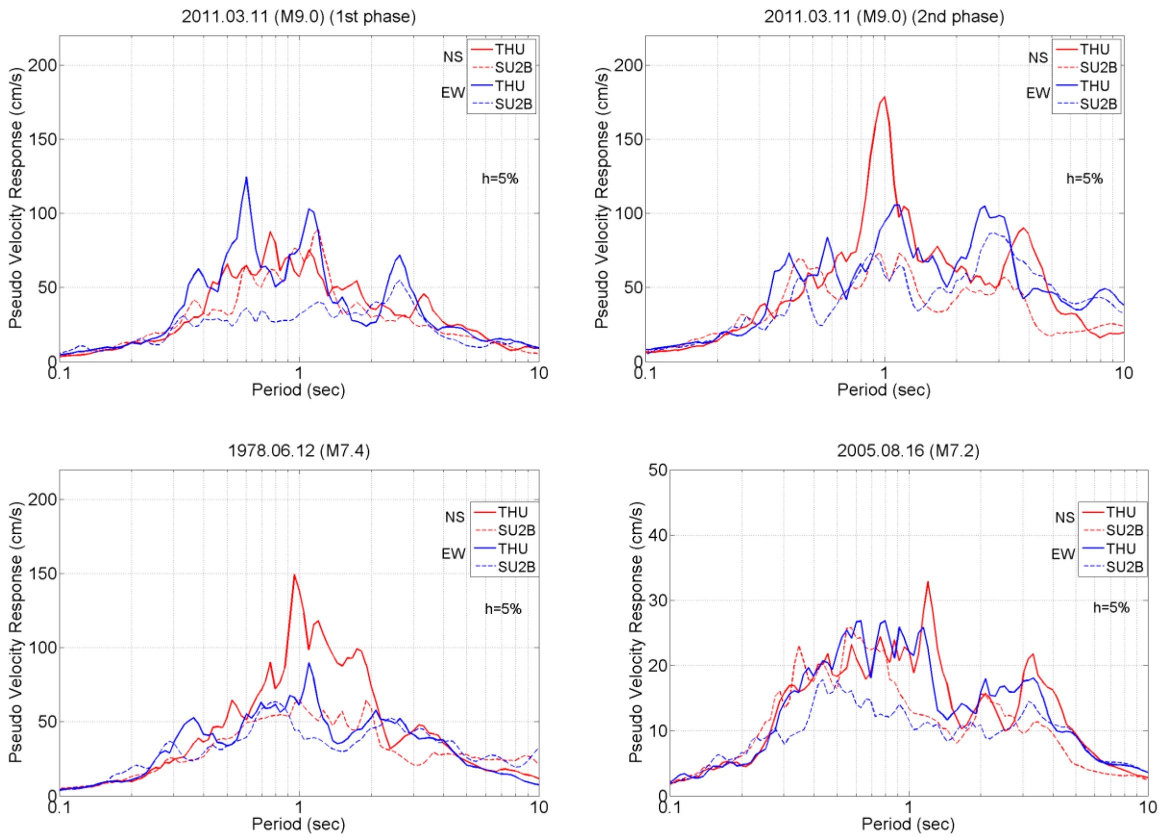

Figure 5.2. Pseudo Velocity Response Spectra characteristics for Miyagi-ken offshore earthquakes

5.2.2.Iwate-ken and Fukushima-ken Inland Earthquakes

The 2008 Iwate-Miyagi Nairiku earthquake (M7.2) is investigated as from northern part spectral amplification shows around 1 sec in horizontal directions and 3-4 sec period range is appeared significantly. In the longer period range, dominant period is longer in EW component than NS component. After the 2011 Tohoku Earthquake there are many aftershocks were observed from south, the 2011.04.11 (M7.0) Fukushima inland earthquake shows spectral range from 0.3 to 1.5 sec is largely amplified, but from 3 sec to 4 sec period show no amplification (Figure 5.3).

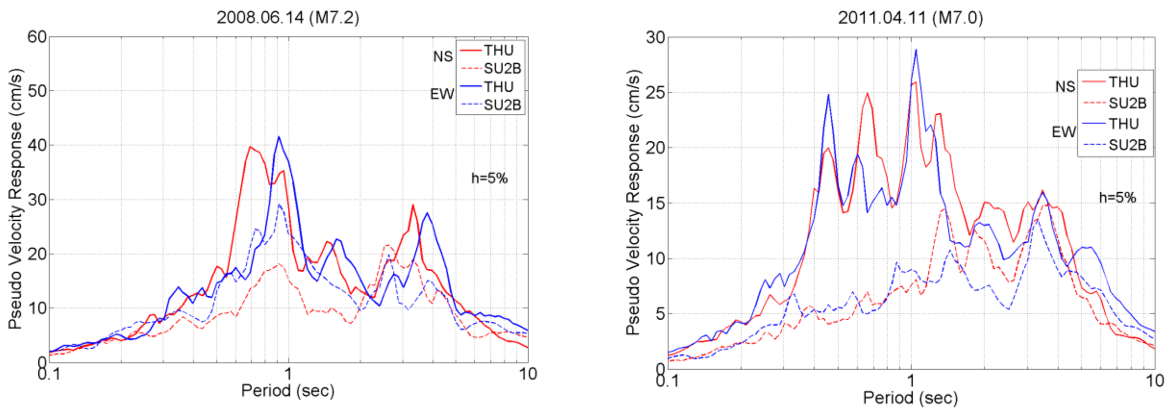

Figure 5.3. Pseudo Velocity Response Spectra characteristics for inland earthquakes

6. CONCLUSIONS

Ground motion amplification characteristics in Sendai area based on the observation records during the 2011 Tohoku earthquake are investigated comparing design spectra at safety limit of Japanese building code. The spectral ground motion amplification characteristics are discussed by dividing the city in 5 zones considering not only surface geology but also deep underground structure. Along a geological section, the observed amplification factors are compared with estimated surface soil amplification factors *Gs*(*T*) specified by the building code. The observed amplifications are consistent with the surface soil amplification factors.

Dominant period at some sites were compared to theoretical dominant period of S-wave incidence based on the existing deep underground geological model. It is recognized that the dominant period of 3 sec in Sendai station area (Theoretical dominant period is 2.0-2.5 for vertical incidence) is not explained by existing geological model. The 4 sec dominant sites are also longer than the model's dominant period.

It is suggested in the irregular geological sites, such as Aobayama hill the ground motion amplification depends not only on azimuth angle but also on incident angle. In order to explain the recognized dominant period, it would be necessary to investigate wave propagation characteristics in dipping layer subjected not only to body waves but also to surface waves.

The ground motion amplification characteristics based on the observed strong motion records would provide very important information for verification of the geological model and seismic micro zoning for earthquake counter measures including seismic design and retrofit of building structures.

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