CHARACTERISTICS OF STRONG EARTHQUAKE MOTIONS OBSERVED AT HACHINOHE CITY HALL

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SUMMARY

The 1994 Sanriku-haruka-oki (Far Off Sanriku) Earthquake and the largest after shock damaged Hachinohe City and the surrounding area. The city is located in northern Japan. Building Research Institute obtained precious strong earthquake motion records at Hachinohe City Hall, in central area of Hachinohe City, during those earthquakes. The peak accelerations of the main shock reached 416 cm/s^2 at the basement floor and 913 cm/s^2 on the top of the building. This paper discusses characteristics of those strong earthquake motion records and dynamic behaviour of this five-storey building during strong earthquake motions. Firstly, we propose an analytical model of soil structure based on the soil survey and perform non-linear analysis to discuss the site effect. The comparison study of the records at the City Hall with the strong ground motions observed at a rock site is also made. The analytical results explain observation records well, and can confirm that earthquake motions were strongly affected by the surface soil layers on the bedrock 100 meters below. Secondly, the effect of the soil-structure interaction is also discussed through the comparison between earthquake motions observed at the basement floor and ones on the ground for small earthquakes. The effect of the soil-structure interaction clearly appears in the higher frequency range than the natural frequency of the building. Remarkable site effect at the Hachinohe City Hall has been discussed through analyses using observed earthquake motions. Effect of soil-structure interaction was also confirmed by comparison study. One of city hall buildings was destroyed by those earthquakes, and redesigned using the base isolation system. We increased the strong motion observation instruments keeping up with reconstruction. The up-to-date observation results are also introduced.

INTRODUCTION

Building Research Institute (BRI), Ministry of Construction, Japan, started the strong motion observation project in 1957. The observation network has been enriched and enlarged in the past forty years. We have obtained a great number of strong earthquake motions including records from the 1964 Niigata Earthquake, the 1978 Miyagi-ken Earthquake, the 1993 Kushiro-oki Earthquake and the 1994 Sanriku-haruka-oki Earthquake. In this paper, we introduce strong motions observed at Hachinohe City Hall for the 1994 Sanriku-haruka-oki Earthquake and discusses amplification of the surface geology and effect of the soil structure interaction.

SITE SITUATION AND GEOLOGICAL CONDITIONS

Hachinohe City is located in the northern part of the main island of Japan and faces the Pacific Ocean. Subduction zone of the Pacific plate down to the Eurasia plate lies east of the northern Japan coast, therefore seismic activity in this area is remarkably high. Hachinohe City has frequently suffered from earthquakes, such as the 1968 Tokachi-oki Earthquake, the 1994 Sanriku-haruka-oki Earthquake and the 1995 Iwate-ken-oki Earthquake.

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Hachinohe City is topographically classified into diluvial tablelands and alluvial lowlands. The City Hall is located on the diluvial plateau with an altitude of 18 meters. Hachinohe City [1] and Building Research Institute (BRI) surveyed the surface geology on the site as shown in Table 1. Gravel or sand layers and silt layers alternately appear beneath the loam deposit. Volcanic tuff with a shear wave velocity of 710 m/s exists at the depth of 98.5 meters.

Table 1: Surface soil structure at Hachinohe City Hall

<table>
<tr><th>No.</th><th>H (m)</th><th>D (m)</th><th>V_P (m/s)</th><th>V_S (m/s)</th><th>ρ (t/m^3)</th><th>Soil Type</th></tr>
<tr><td>1</td><td>0.80</td><td>0.80</td><td>-</td><td>-</td><td>-</td><td>Fill</td></tr>
<tr><td>2</td><td>2.00</td><td>2.80</td><td>1210</td><td>111</td><td>1.45</td><td>Loam</td></tr>
<tr><td>3</td><td>6.20</td><td>9.00</td><td>1390</td><td>144</td><td>1.45</td><td>Loam</td></tr>
<tr><td>4</td><td>1.50</td><td>10.50</td><td>1630</td><td>335</td><td>2.00</td><td>Gravel</td></tr>
<tr><td>5</td><td>1.90</td><td>12.40</td><td>1390</td><td>235</td><td>1.70</td><td>Clayey Fine Sand</td></tr>
<tr><td>6</td><td>2.00</td><td>14.40</td><td>1620</td><td>387</td><td>2.00</td><td>Gravel</td></tr>
<tr><td>7</td><td>2.85</td><td>17.25</td><td rowspan="4">1460</td><td>243</td><td>1.71</td><td>Silt</td></tr>
<tr><td>8</td><td>1.15</td><td>18.40</td><td>319</td><td>1.90</td><td>Fine Sand</td></tr>
<tr><td>9</td><td>5.00</td><td>23.40</td><td>266</td><td>1.66</td><td>Silt</td></tr>
<tr><td>10</td><td>4.70</td><td>28.10</td><td>293</td><td>1.70</td><td>Silt</td></tr>
<tr><td>11</td><td>1.60</td><td>29.70</td><td>1540</td><td>370</td><td>1.90</td><td>Fine Sand</td></tr>
<tr><td>12</td><td>3.70</td><td>33.40</td><td>2200</td><td>790</td><td>2.00</td><td>Gravel</td></tr>
<tr><td>13</td><td>10.90</td><td>44.30</td><td rowspan="2">1630</td><td>415</td><td>1.80</td><td>Silt</td></tr>
<tr><td>14</td><td>13.00</td><td>57.30</td><td>407</td><td>1.90</td><td>Fine Sand</td></tr>
<tr><td>15</td><td>3.40</td><td>60.70</td><td rowspan="2">1680</td><td rowspan="2">560</td><td>1.85</td><td>Silt</td></tr>
<tr><td>16</td><td>3.50</td><td>64.20</td><td rowspan="2">1.95</td><td>Silty Fine Sand</td></tr>
<tr><td>17</td><td>4.60</td><td>68.80</td><td>1690</td><td>550</td><td>Fine Sand</td></tr>
<tr><td>18</td><td>9.30</td><td>78.10</td><td>1590</td><td>480</td><td>1.85</td><td>Sandy Silt</td></tr>
<tr><td>19</td><td>5.50</td><td>83.60</td><td>1670</td><td rowspan="2">560</td><td rowspan="3">2.00</td><td>M. Sand</td></tr>
<tr><td>20</td><td>6.20</td><td>89.80</td><td>1700</td><td>Fine Sand</td></tr>
<tr><td>21</td><td>7.10</td><td>96.90</td><td>1880</td><td>590</td><td>Fine Sand</td></tr>
<tr><td>22</td><td>1.70</td><td>98.60</td><td rowspan="3">2050</td><td rowspan="3">710</td><td>1.95</td><td>Tuff</td></tr>
<tr><td>23</td><td>3.60</td><td>102.20</td><td>2.20</td><td>Sand Stone</td></tr>
<tr><td>24</td><td>2.50</td><td>104.70</td><td>1.95</td><td>Tuff</td></tr>
</table>

H: Thickness, *D*: Depth, V_P: P-wave Velocity, V_S: S-wave Velocity, ρ: Density.

INSTRUMENTATION

BRI has started strong earthquake motion observation at Hachinohe City Hall in 1979. In 1993, we removed old analogue instruments from the then main building and installed a digital instrument to the then annex building. This instrument is called SMAC-MD and can have two external sensors in addition. The main instrument is set up at the top floor (06F), and an external sensor is equipped at the basement floor (B1F).

In 1998, Hachinohe City reconstructed the annex building with base isolation system and the old building is called main building since. BRI has installed a new array observation system to the building and the ground in 1999. The system is composed from a SMAC-MDU accelerograph, three sensors in the building and three sensors in the borehole. Sensors in the borehole are placed 1 meter (GL), 30 meters and 105 meters (G105) in depth. Figure 1 shows the promises of Hachinohe City Hall and the sensor configuration. Brief specifications of SMAC-MD and SMAC-MDU instruments are described in Table 2. Both have wide dynamic range and high reliability.

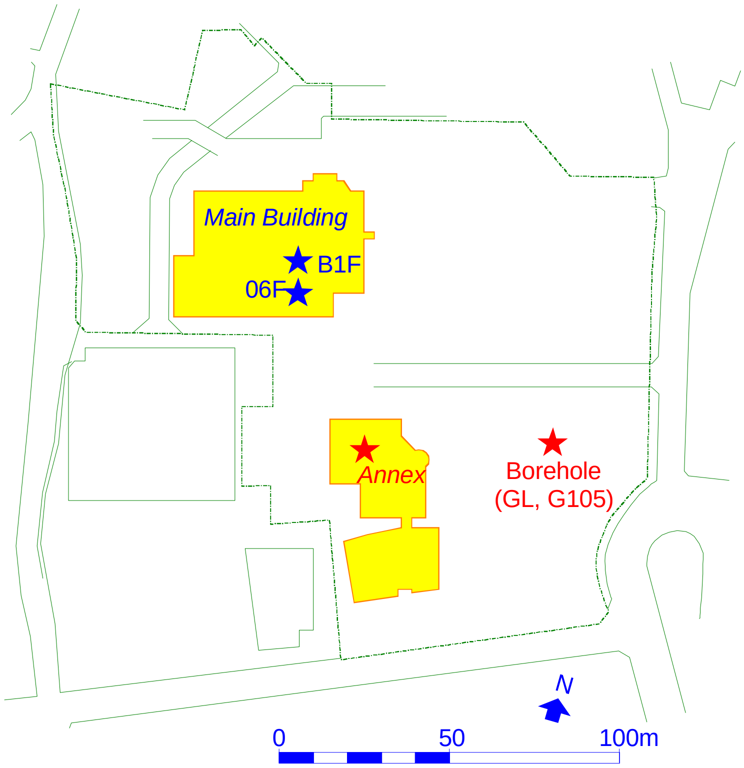

Figure 1: Ground Plan and Sensor Configurations at Hachinohe City Hall

Table 2: Specifications of Instruments

Model	**SMAC-MD**	**SMAC-MDU**
Sensor	Servo	Servo
Year Developed	1988	1997
Processing System	Digital (16-bit)	Digital (24-bit)
Recording Medium	Memory Card	PCMCIA Flash Memory Card
Frequency Range	0.02 ~ 30 Hz	DC ~ 30 Hz
Acceleration Range	±1000 cm/s^2	±2000 cm/s^2
Sensitivity	0.03 cm/s^2/digit	0.0025 cm/s^2/digit
Start Level	0.5~32 cm/s^2	0.1 ~ 99.9 cm/s^2
Sampling Frequency	50, 100 or 200 Hz	50, 100 or 200 Hz
Number of Components	3 ~ 9 (max.)	3 ~ 18 (max.)
Delay Time	10 sec.	0 ~ 60 sec.
Size (W×D×H)	40 cm × 42 cm × 21 cm	40 cm × 42 cm × 21 cm
Weight	20 kg	20 kg

OBSERVED EARTHQUAKE RECORDS

Table 3 lists earthquakes and peak accelerations of the records that are discussed in this paper. The Sanriku-haruka-oki (Far off Sanriku) Earthquake (EQ1) of December 28, 1994 is the most recent disastrous earthquake [2]. Hachinohe City and surrounding area suffered from the earthquake. The old main building of Hachinohe City Hall was also damaged by the earthquake and was demolished. In the next building, a notable record with large peak accelerations as shown in Table 3 was obtained.

Another earthquake (EQ2) is the first record after the borehole installation, although a moderate one. This is useful to investigate effect of surface geology and soil-structure interaction.

Table 3: List of earthquakes and observed peak accelerations

No.	Origin Time	*h* (km) M_{JMA}	Site	Δ (km)	Place	Peak accelerations (cm/s^2)		
						N164°E	N254°E	UP
EQ1	1994/12/28 21:19	0 7.5	HCH	191	B1F	415.9	319.7	118.7
					6F	962.6	718.1	227.1
			HMO	188	GL	602.3*1	488.4*2	96.1
EQ2	1999/05/13 02:59	104 6.4	HCH	338	B1F	16.3	12.7	7.3
					06F	57.6	47.6	11.3
					GL	48.3	44.5	15.7
					G105	9.0	6.4	5.2

h: Focal Depth, M_{JMA}: Japan Meteorological Agency (JMA) Magnitude, Δ: Epicentral Distance.
*1: N-S component, *2: E-W component.

CHARACTERISTICS OF GROUND MOTIONS

Fourier amplitude spectra of accelerations at Hachinohe City Hall (HCH) are compared with ones at Hachinohe Meteorological Observatory, Japan Meteorological Agency (HMO) for EQ1 in Figure 2. HMO is located 3.3 kilometres to the Northeast of HCH and on the hard rock covered with loam with a thickness of 10 meters [3]. Conspicuous differences between HCH and HMO are appeared in the frequency range from 0.7 Hz to 5 Hz on Fourier amplitude spectra. While spectra of records at HCH have remarkable peaks at 1 Hz, ones at HMO are superior in the higher frequency range between 2.5 Hz and 5 Hz.

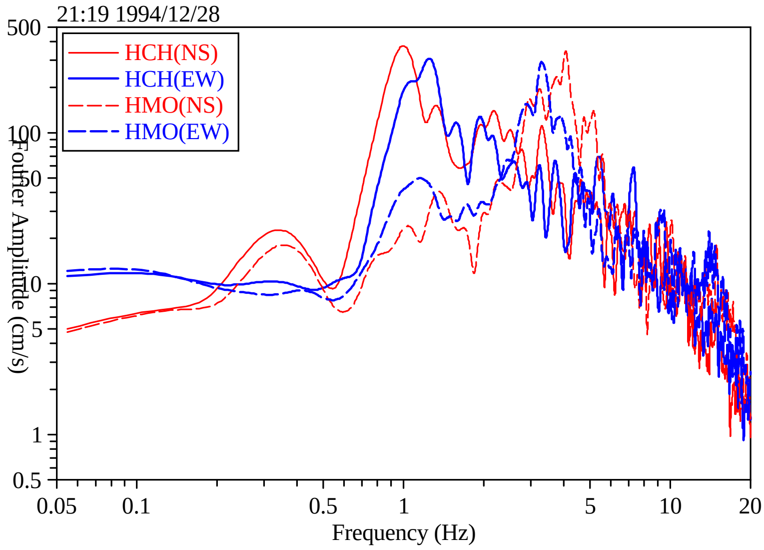

Figure 2: Fourier Amplitude Spectra of Ground Motions Observed at HCH and HMO for EQ1

Figure 3 shows Fourier amplitude spectra of earthquake motions at GL and at G105 for EQ2. Amplitudes at GL are generally predominant, especially at 1.2 Hz and 3 to 4 Hz. There are no large differences caused by the directions. Fourier amplitude ratios of accelerations on the ground to ones beneath the borehole (GL/G105) and a theoretical transfer function are plotted in Figure 4. These have clear peaks at 1.2 Hz and 2.8 Hz to 3.1 Hz, and the theoretical transfer function shows good agreement with observed spectral ratios. Surface soil layers with a thickness of 105 meters cause prominent amplifications of earthquake motions at frequencies of around 1.2 Hz and around 4 Hz.

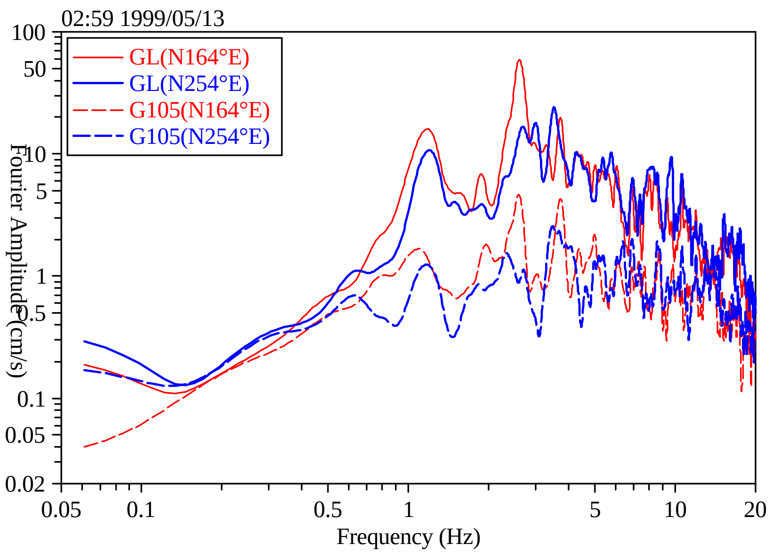

Figure 3: Fourier Amplitude Spectra of Ground Motions Observed at HCH for EQ2

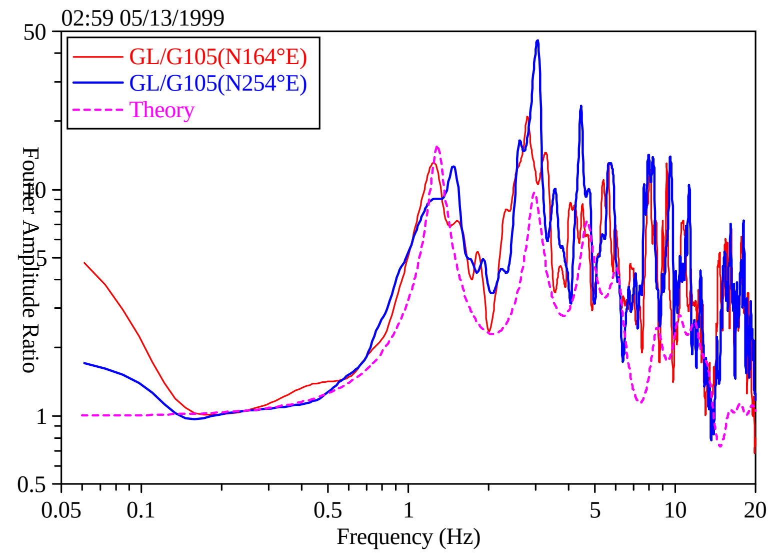

Figure 4: Fourier Amplitude ratios of Ground Motions at GL to ones at G105 for EQ2

NON-LINEAR SEISMIC RESPONSE OF SURFACE SOIL LAYERS

In order to verify the geological model and to evaluate plastic behaviour of soil layers, non-linear seismic response analysis using Osaki's program [4] is made. Authors assumed that the volcanic tuff 10 meters below HMO site continues to the bed rock 105 meters under HCH. Strong motion records at HMO were corrected using transfer function to remove effects of 10-meter-thick sediment, and is used as the input earthquake motions for the dynamic response analysis.

Fourier amplitude spectra of calculated accelerations at B1F of HCH are compared with observed ones in Figure 5. Analytical results show good accord with observed ones, consequently we judge surface soil layers was modelled well. Maximum shear stress reached 0.1 percents in the silt layers.

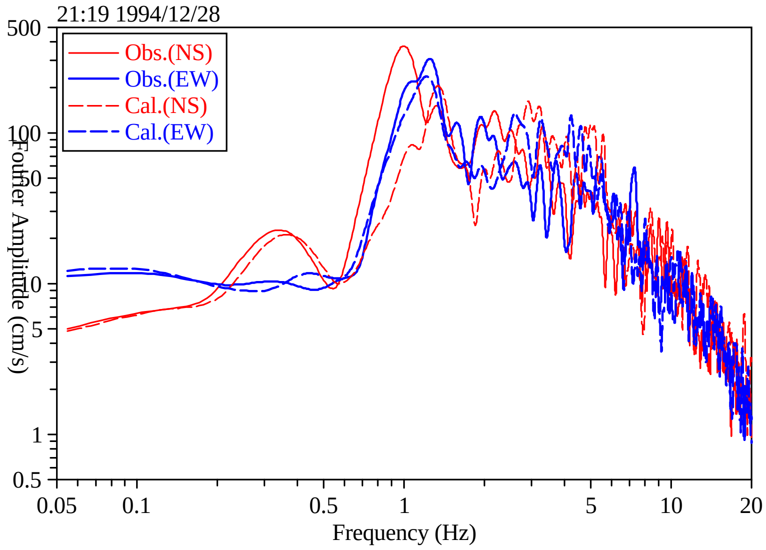

Figure 5: Fourier Amplitude Spectra of Observed and Calculated Ground Motions at HCH for EQ1

EFFECT OF SOIL STRUCTURE INTERACTION

Earthquake motions recorded in a building include effects of soil-structure interaction (SSI). SSI effects are investigated through spectral analyses of records for EQ2. Fourier amplitude ratios B1F/GL, 06F/GL and 06F/B1F are plotted in Figure 6. In the N254°E direction, the first natural frequency of SSI system can be clearly recognised as 2.6 Hz from amplitude ratio 06F/GL. Spectral ratio 06F/B1F in the N254°E direction also has an apparent peak at 2.85 Hz. This is the first natural frequency of the building system including rocking effect. However the natural vibration in the N164°E direction of the SSI system is obscure. The first natural frequency of the building system is 2.9 Hz in the N164°E direction.

Spectral ratios B1F/GL in both directions roughly become half in the frequency range higher than the first natural frequency. This is one of reasons that peak accelerations at B1F are thirty to forty percents of ones at GL (see Table 3).

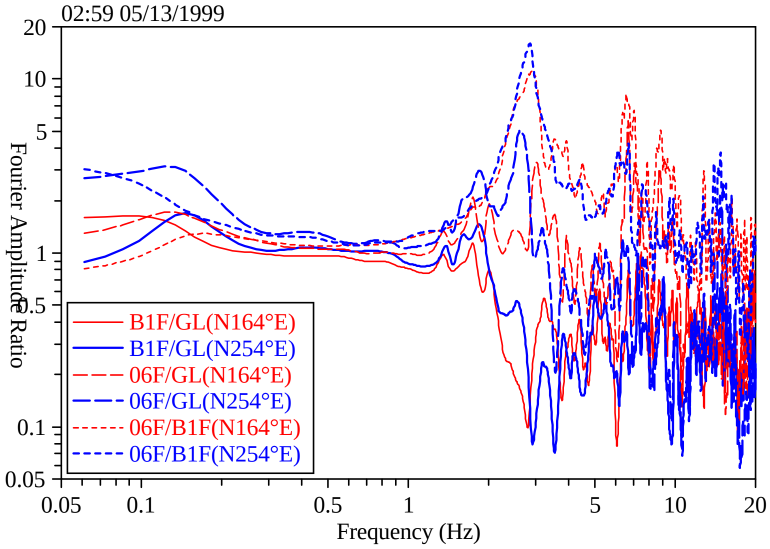

Figure 6: Fourier Amplitude Ratios B1F/GL, 06F/GL and 06F/B1F at HCH for EQ2

CONCLUSIONS

Authors have discussed characteristics of strong earthquake motion records observed at Hachinohe City Hall and summarise results as follows.

- Ground motions at Hachinohe City Hall have prominence in the frequency range of 1 to 1.4 Hz. This originates from the soil sediment with a thickness of 100 meters.

- Non-linear seismic response analysis of the surface soil layers brought about good accord between calculated result and observed one. Our soil-structure model is appropriate to the actual condition.

- Effect of the soil structure interaction was observed through the comparison between strong motion records in the building and ones on the free field. The effect appears in the higher frequency and makes acceleration amplitudes at the basement floor small.

We have added strong motion instrument to the annex building and in the borehole. The accumulation of high-quality records and clarification of seismic input mechanism to buildings are expected.

REFERENCES

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