

# OBSERVATION AND MODELING OF EARTHQUAKE SITE RESPONSE IN THE SENDAI BASIN, JAPAN

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## SUMMARY

Sendai City suffered severe damage due to the 1978 Miyagiken-Oki Earthquake. Since the earthquake, Sendai City has extended into areas composed of softer soils, increasing the anxieties of more devastating disaster by a great earthquake in the near future. A panel of the central government predicts that there could be a great earthquake near Sendai with a high probability of about 88 percent within 20 years from now on. Sendai City is also characterized by its irregular ground structures. In general, the irregularity of ground structure has an effect of amplifying on ground motions, as indicated by the experience of the 1995 Kobe Earthquake. This means that ground motions in Sendai are affected by such structures and thus could culminate in great disaster. This paper discusses comparatively both results of observed motions and response analyses that have been performed in the Sendai City area.

## INTRODUCTION

A panel set up by the central government of Japan, the Headquarters for Earthquake Research Promotion [1], predicts that there could be a great earthquake of a magnitude of 7.5 or so off the coast of Miyagi Prefecture with a high probability of about 88 percent within 20 years from now on. Sendai City, which is the capital and the biggest city with a population of one million in Miyagi Prefecture, experienced severe damage due to the 1978 Miyagiken-Oki Earthquake that occurred about 25 years ago in an area similar to the probable earthquake (Okamoto [2]). The city's residential areas have recently extended to lands composed of soft soils with the increase of its population. In addition, it has a typical basin structure of sediments that could lead to irregularly extreme amplifications of ground motions during earthquakes. Amplifications of strong-ground motions within sedimentary basins have long been viewed to be a main cause of damage during great earthquakes. The enormous disaster in Kobe City during the 1995 Hyogoken Nanbu Earthquake is sometimes cited as one of example caused by such a basin-structure effect. Sendai City is thus highly vulnerable to great earthquakes in light of the obvious similarity in the basin structure to the Kobe situation. In order to investigate strong-ground motions in Sendai, we installed there an array observation system of ground motions in 1997 (Kamiyama and Shoji [3]). The array system, named Small-Titan, consists of 20 observation stations and one control center. Stimulated by the high

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seismicity in the Sendai district, the system has obtained many motion records resulting from a total of 250 earthquakes as of February in 2004.

This paper first discusses observation results of ground motions in the Sendai basin from the point of view of local site effects, showing that amplifications of ground motions vary from site to site and are remarkable in the soft deposit areas of the basin. The differences in amplifications between locations of the soft deposit areas are also analyzed. This analysis leads to the importance of the edge effects of basin structure on the ground motions of the soft deposit areas. In order to make clear the mechanism of the edge effects, we model the Sendai basin using a two-dimensional Pseudo-Spectral Method. Based on the model of basin structure, we make two-dimensional analyses of ground motions and compare the analyzed results with the observed. Comparisons show that the edge effects play an important role in amplifying motions in the soft deposit area of basin structure.

## **OBSERVATION SYSTEM OF GROUND MOTIONS AND SITE CONDITIONS**

Figure 1 shows a digital elevation map of the Sendai area and observation locations of the Small-Titan array. The Sendai area is roughly divided into two categories of geology by an active fault named the Nagamachi-Rifu Fault that runs through its central part from southwest to northeast. The surface trace of the fault coincides with the southwest-to-northeast boundary line of the lowest elevation in Figure 1. The northwest part demarcated by the fault trace consists mainly of diluvial deposits while alluvial sediments cover the opposite part across the fault. Figure 2 illustrates geological cross sections along the lines tabbed 39 and 41 in Figure 1. In Figure 2, S-wave velocity, P-wave velocity, density  $\rho$  and quality factor Q are given to represent the differences in geology of each layer. Figure 2 shows a clear basin structure of



Figure 1. Map of the Sendai area and observation sites of Small-Titan



Figure 2. Cross-sections of geology along line 31 and line 41.

sediments characterized by the sharp discontinuity between the diluvial deposits and alluvial soils. The solid circles in Figure 1 indicate the observation points of the Small-Titan system. As shown in Figure 1, the system consists of 20 observation stations in total and one control center that is located near the TITK site. The system has typically a profile of simple extended array equipped with real-time and on-line transmission devices. The control center constantly monitors the seismographs at the observation stations and acquires automatically strong-motion data by a telemetry system that uses the fast digital communication network, ISDN, served by the NTT (Nippon Telegraph and Telephone Corp.). Each station observes ground motions in the three directions of north-to-south(NS), east-to-west(EW) and up-to-down(UD) while their triggering systems for recording are independent of one another so as to be compatible to the level of their background noises. The observation system basically aims at obtaining earthquake motions simultaneously at various kinds of sites during different types of earthquakes. Its average station-to-station distance is about 4 km and each station was installed at various kinds of soils to

effectively obtain local site effects. Especially, we placed emphasis on the total layout of observation stations to explore various effects due to the basin structure. Representative stations for such an exploration along the cross-section lines of 39 and 41 are displayed in Figure 2.

#### GENERAL FEATURES OF OBSERVED GROUND MOTIONS

Small-Titan has succeeded in obtaining simultaneously earthquake records at all the stations during a total of 42 earthquakes for the past 6 years due to the high seismicity in the Pacific coast area of Japan. As an example of these observed ground motions, the records obtained at each station along the line named 39 in Figure 2 are plotted for the EW component in Figure 3. They were obtained during an earthquake that occurred with a magnitude of 6.2 off the coast of Miyagi Prefecture and will be used for the simulation analyses in the later section. Figure 3 indicates that each record differs in their amplitudes and waveforms from station to station in response to respective site conditions. Ground motions obtained at sites in the alluvial area generally provide larger amplitudes compared with those in the diluvial side. In addition, ground motions at sites located in the alluvial area also vary sensitively reflecting their soil conditions. Especially, the records at the alluvial site such as CCHG and ARAH have obvious later-phases after their main parts of motions.

Figure 4 shows a distribution of normalized maximum-acceleration among the EW, NS and UD components at each site along the line named 39 during the 42 earthquakes. The distribution in Figure 4 was normalized by the maximum amplitudes at site SAKR to represent relative variations of maximum amplitudes at each site. The distribution also includes an average of normalized maximum for all the earthquakes as well as the relative maxima for each earthquake. Figure 4 reveals that the amplitudes of ground motions in the alluvial area amount to about 3 times on an average against those in the diluvial area.



Figure 3. Observed records at sites along line 39



Figure 4. Normalized maximum accelerations at the sites along line 39

#### THEORETICAL ANALYSES OF EARTHQUAKE RESPONSES

In order to theoretically investigate the characteristics of observed ground motions, we carried out response analyses for the Sendai basin in Figure 2 using a two-dimensional Pseudo-Spectral Method (PSM). PSM is a numerical technique for obtaining the time-domain solutions for the equations of motions so that spatial derivatives are analyzed in the wave-number domain utilizing the spectrum transfer whereas temporal derivatives are estimated by means of the finite difference approximation. Its spatial derivatives of motion parameters have an unlimited increasing order of accuracy compared with those by widely used methods such as the Finite Element Method. Such a character of PSM makes it possible to widen the spacing of grid points, resulting in inexperienced computation (Kamiyama and Satoh [4]). We modeled the basin structures in Sendai into a two-dimensional problem. Such a two-dimensional analysis of earthquake response can be separately dealt with as the anti-plane problem (the SH wave problem) and the in-plane problem (the P-SV wave problem). We formulated both problems using a twodimensional PSM in terms of particle velocities and stresses for each motion-equation for SH and P-SV waves. Details of the PSM technique were presented in another article [4]. We performed two different kinds of earthquake response analyses for the 39 and 41 structures: one is analyses in which a Ricker wavelet was used for its incident waves and the other is simulations using observed records as their incident motions. The former aimed at giving insight into the mechanism of wave propagation for basin structures of the 39 and 41 cross-sections because the Ricker wavelet is available to control the contents



Figure 5. Response results of horizontal acceleration on the ground surface at representative points in the cross-section of line 41 for a Ricker wavelet incidence of SH wave

of amplitude and period for response analysis. The purpose of the latter, on the other hand, is to compare the simulated motions with the observed records by Small-Titan. In this paper, the former theme focused on the structure along the line named 41 and the latter was dealt with principally in the 39 structure. We discretized both structures of 39 and 41 so as to keep the stable conditions of analysis: the grid-spacing intervals are 5 m and 2 m, respectively, in the horizontal and vertical directions with a total number of grids of 4096 and 128 in each direction whereas the time increments are 0.001 sec for the SH problem and 0.00025 sec for the P-SV problem. Note that we carried out these analyses on the condition of vertically incident S wave from the base layer in the 39 and 41 basin structures.

Figure 5 shows response results of horizontal acceleration on the ground surface at representative points in the 41 cross-section for a Ricker wavelet incidence of SH wave with its central period of 0.3 sec and peak acceleration of 100 gal. Figure 5 represents waveforms at the points on the surface with an interval of 500 m in the horizontal direction. Figure 5 indicates that responses of ground motions vary remarkably from point to point depending on the subsurface structures of sediments. Note that the irregularities of layer interfaces produce some horizontally propagating motions and cause, as a result, such a remarkable variation of motions dependent on sites. The horizontal propagation waves have an obvious character of surface waves produced secondarily due to the existence of irregular layers. Figure 5 also shows a sensitive difference in their waveforms even for the alluvial sediment sites probably reflecting each condition of soils. Such a difference is given in Figure 6, showing the peak accelerations of response motions at each point. Figure 6 indicates that SH waves are amplified by about 3 times in the alluvial area against the diluvial area, but the constructive interference between the direct waves propagating up through the sediments and the horizontally traveling waves differs at each site for the alluvial sediments, resulting in an extreme acceleration at a specific point. This situation is similar even in the P-SV wave problem, though being not shown here because of space consideration.



Figure 6. Maximum accelerations of horizontal response motions on the ground surface at representative points in the cross-section of line 41 for a Ricker wavelet incidence of SH wave

#### COMPARISONS BETWEEN RESPONSE ANALYSES AND OBSERVED RECORDS

We carried out earthquake response analyses for the 39 cross-section using the observed records at the SAKR station as their incident motions. As shown in Figure 2, the SAKR station is situated at the outcrop of the base layer so that its observed records constitute the input motions for our response analyses. In applying the SAKR records to our analyses, the three components of motions were synthesized to obtain the SH and SV components for the 39 cross-section, assuming that S waves travel along the line connecting the observation station with the epicenter. In addition, we used these synthesized components as the input motions in the base layer after halving their amplitudes to take the free-surface effect into account. The analysis earthquake, which provided the observed motions in Figure 3, represents a magnitude of 6.2, epicentral distance of 100 km and hypocentral depth of 50 km. The earthquake-source conditions may satisfy the assumption of analysis in which the incident waves in the base layer propagate up vertically.

The analyzed horizontal acceleration responses showed similar characteristics to Figure 5 for the SH case. That is, the basin-edge effects to locally produce the horizontally traveling waves exist clearly even in the responses using the observed input motions. As a result, the response motions are more complicated due partially to the constructive interference of these horizontal-propagation waves with the direct up traveling waves. Figure 7 shows comparisons of the analyzed motions with the observed records at station MOGA. Figure 8 also shows a similar comparison at station CCHG. On the other hand, comparisons of spectra between the analyzed motions and observed records are shown in Figure 9 and Figure 10, respectively, for the MOGA station and the CCHG station. There is a fairly good agreement between the analyzed and observed motions in their spectra as well as their waveforms for both stations, meaning that our response analyses are valid to some extent.



Figure 7. Comparisons of waveforms between the analyzed motions and observed motions at MOGA site for SH wave (upper) and SV wave (lower)



Figure 8. Comparisons of waveforms between the analyzed motions and observed motions at CCHG site for SH wave (upper) and SV wave (lower)

#### **CONCLUDING REMARKS**

Observed ground motions by the array system of Small-Titan indicate that Sendai City has quite a different feature of amplifications between its alluvial area and diluvial area. Ground motions in the alluvial area show larger amplifications and longer duration compared with those in the diluvial area. In addition to such a difference between both areas, the ground motions in the alluvial area also vary from site to site depending on their subsurface structures. The effects of the basin sediments mainly bring about these characteristics of ground motions. We confirmed theoretically such effects by a numerical modeling of the Sendai basin using the two-dimensional Pseudo-Spectral Method. The lateral inhomogeneity in the basin structure produces horizontally traveling surface waves so as to cause a constructive interference



Figure 9. Comparisons of spectra between the analyzed motions and observed motions at MOGA site for SH wave (left) and SV wave (right)



Figure 10. Comparisons of spectra between the analyzed motions and observed motions at CCHG site for SH wave (left) and SV wave (right)

with the direct vertically propagating waves, culminating in extremely large amplifications for the alluvial sediments.

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