1469

A HIGH-DENSITY ARRAY OBSERVATION SYSTEM SMALL-TITAN: AN INTRODUCTION AND IT’S STRONG-MOTION RECORDS

Yuichi SHOJI[1] **And Makoto KAMIYAMA**[2]

SUMMARY

An array observation system with high-density, named Small-Titan, was installed in Sendai City, Japan in 1998. The objective of thi s paper is to outline the network system and to discuss strong-motion records obtained during a typical near-distance earthquake. The system, Small-Titan, consists of 20 observation stations and one control center that are both situated in Sendai City. The average station-to-station distance is about 4 km and each station was installed at various kinds of soils to effectively detect local site conditions. 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. Because of its fastness of data acquisition, the observation system is applicable to the intelligent real-time system for earthquake disaster reduction. Since its completion in June 1998, the observation system has obtained several strong-motion records. Especially, the system observed a maximum acceleration of 455 gal during an earthquake with a magnitude of 5.0 that occurred on September 15, 1998 within an epicentral distance of about 5km. We made various analyses to the records: Fourier spectrum analysis, spectral ratio analysis, non-stationary spectrum analysis and so on. The strong-motion records at the 20 stations showed quite different features depending not only on their soil conditions but also on the positions relative to the epicenter. At the same time, source effects such as the directivity of faulting were clearly picked up in those records. It is concluded that local soil conditions determine the spectral characteristics of strong motions more effectively than earthquake source effects. On the other hand, source effect, especially the directivity effect of faulting contributes strongly to the maximum amplitude of time history.

INTRODUCTION

Many seismic observation systems have been developed throughout Japan since the 1995 Great Hanshin Earthquake[Kinoshita, 1998]. This trend is based on a lesson learned from the earthquake. That is, the catastrophe taught us that the “accumulation of observation” is essential and appropriate for the purpose of earthquake disaster mitigation, even though it seems to be a detour. Since seismic motions depend primarily on the effects of earthquake source, propagation path and local site characteristics through quite complicated processes, it is important to design and install observation system so as to effectively analyze them. In this context, an array observation system is ideal because it enables a systematic understanding of the three effects. The array observation systems of ground motions are generally classified into two categories based on their density and configuration: the “local laboratory array” and the “simple extended array” [Iwan W. D., 1979]. The latter is more advantageous from the point of view of cost performance. In addition, this type’s system can be also used as a disaster mitigation system in real-time if it is equipped with devices for instant transmission of data.

The Tohoku Institute of Technology, which is located in Sendai City, Japan, initiated a research project on the usage of earthquake observation system in 1997. This is one of a more large-scale project, the “High-tech Research Center Projects” that is aided in part by the Ministry of Education, Culture and Science in Japan. The

[1] *Dept of Design, Tohoku Branch, DPS Bridge Works Co., Ltd., Sendai, JapanEmail: sen-dps@mxa.mesh.ne.jp*
[2] *Dept of Civil Engineering, Tohoku Institute of Technology, Sendai, JapanEmail: mkamiyam@titan.tohtech.ac.jp*

observation system has typically a profile of the simple extended array equipped with real-time and on-line transmission lines. This basically aims at obtaining earthquake ground motions simultaneously at various kinds of sites during different types of earthquakes. At the same time, this system places importance on the development of real-time disaster mitigation with aid of its characteristic profile. The observation system, which was named Small-Titan (Strong Motion Array of Local Lots by the Tohoku Institute of Technology Area Network), was completed at the end of 1997 fiscal year and test observations started in June, 1998. Since its starting of observation, the system has obtained several strong-motion records. Especially, it observed a maximum acceleration of 455 gal during an earthquake with a magnitude of 5.0 that occurred on September 15, 1998 within an epicentral distance of about 5km. It is a rare case that such a near-distance earthquake triggered this kind of array observation, so the observed records are quite valuable to investigate the strong-motion characteristics near the source. This paper outlines the observation system and discusses the strong-motion records obtained during the typical near-distance earthquake.

OBSERVATION SYSTEM OUTLINE

The system, Small-Titan, consists of 20 observation stations and one control center that are both situated in Sendai City. The average station-to-station distance is about 4 km and each station was installed at various kinds of soils to effectively detect local site conditions. 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. Because of its fastness of data acquisition, the observation system is applicable to the intelligent real-time system for earthquake disaster reduction.

The Sendai City zone was selected as a model field for Small-Titan mainly for the following reasons:

(1) The Sendai region exists near Sanriku-oki (the offing of Sanriku), Miyagi-ken-oki (the offing of Miyagi Prefecture) and Fukushima-ken-oki (the offing of Fukushima Prefecture) that all constitute one of Japan’s most eminent area repeatedly triggering large inter-plate earthquakes. Moreover, the Nagamachi-Rifu Fault, an active fault with an activity degree of 1, runs across the center of Sendai City from the southwest to the northeast. These facts suggest a high seismicity in this region.
(2) There is a high chance of obtaining seismic motion data due to two different types of earthquake: inter-plate earthquakes and intra-plate earthquakes.

(3) The Sendai region shows a clear contrast in geology across the Nagamachi-Rifu Fault: a diluvial plateau in the west and an alluvial lowland in the east, making it easier to evaluate the local site effects, especially the effect of laterally inhomogeneous soils on seismic motions.

(4) The region had been struck by the Miyagi-ken-oki Earthquake in 1978 with enormous damage to various kinds of structures. The damage experiences provide us with data possible to examine the relations between seismic motions and damage.

OBSERVATION SITE LAYOUT AND SOIL TYPES

Figure 1 shows the layout of the observation sites. These stations were deployed taking the following points into account:

(1) The Sendai City region was covered as evenly as possible so as to give greater efficiency in applying the observation system to the disaster mitigation system.

(2) Various kinds of soils were selected so that the local site effects on seismic motions could be effectively detected.

(3) Man-made lands that had been developed for housing lots were included as an observation site based on the damage experience due to the Miyagi-ken-oki Earthquake in 1978.

(4) The observation sites were deployed to detect systematically the effect of laterally inhomogeneous soils on ground motions. Namely, the linear cross sections along the several observation sites provide a typical structure of laterally inhomogeneous ground.

(5) The Nagamachi-Rifu Fault recently has been causing small earthquakes that may be considered to be pre-earthquakes for a possible large earthquake in the future. If the fault triggers such a large earthquake, the observation sites here enable to detect various source effects such as the radiation pattern, directivity, inhomogeneity of faulting and so on.

All the observation stations were installed on school campuses with aid of the educational organizations because it was easy to obtain their approval for setting and the observation system here was originally intended to apply to the local disaster mitigation system. In Sendai City, schools are allocated as a shelter in case of emergency associated with large earthquakes, therefore the seismic information presented by the observation system may enhance the function for the city's earthquake disaster mitigation.

In developing an observation system characterized as the simple extended array, its most important strategy is to select a site as an appropriate reference site so that the amplification factors at each site can be effectively estimated. In this observation system, the No.1 site was selected to meet the reference site condition on account that it lies on the outcrop consisting of the andesite deposit, called the Takadate layer. According to geological surveys, the layer is considered to deposit at a depth of about 500m in the central part of Sendai City.

In summary, the observation sites are classified in terms of soil types as follows:

Bed rock: site 1

Diluvial plateau: sites 7, 8, 9, 10, 14, 15, 16 and 20

Alluvial lowland: sites 2, 3, 4, 5, 6, 11, 12, 17 and 18

Diluvium-alluvium boundary: sites 10, 13 and 19

Man-made land: sites 7, 9 and 16

Alluvial soft soils: sites 5 and 18

Figure 2 shows a typical example of geologic profile along a cross section line normal to the Nagamachi-Rifu Fault together with the corresponding observation sites. It can be seen from Figure 2 that Small-Titan was designed with due consideration toward the effect of lateral inhomogeneous soils on ground motions.

These strong-motion records at the 20 stations show quite different features depending not only on their soil conditions but also on the positions relative to the epicenter. As an example of acceleration records dependent on soil conditions, the E-W records of the observation sites along the cross section of ground shown in Figure 2 are reproduced in Figure 5. We can see from Figure 5 that there are conspicuous differences in the waveform between the sites in the west and sites in the east across the Nagamachi-Rifu Fault. In particular, the east sites tend to show larger amplitudes and longer duration even though they are further far from the epicenter, compared with the west sites. These phenomena are consistent with the geological differences shown in the cross section of ground. On the other hand, Figure 3 demonstrates that the maximum amplitude of acceleration among all the observation sites is realized at the No.20 site with a peak value of 455 gal. This site has almost an identical epicentral distance and similar soil conditions to the other sites like No.7 and No.8, indicating a specific reason for the maximum of acceleration. Note that the No.20 site shows a smaller duration of its main motions whereas it shows larger peak of amplitude, especially compared with the No.7 site. Hence such a character of record's duration and peak suggests that the faulting directivity peculiar to the source brought about the peak amplitude at site No.20. This interpretation will be discussed later in connection to the non-stationary spectral analysis.

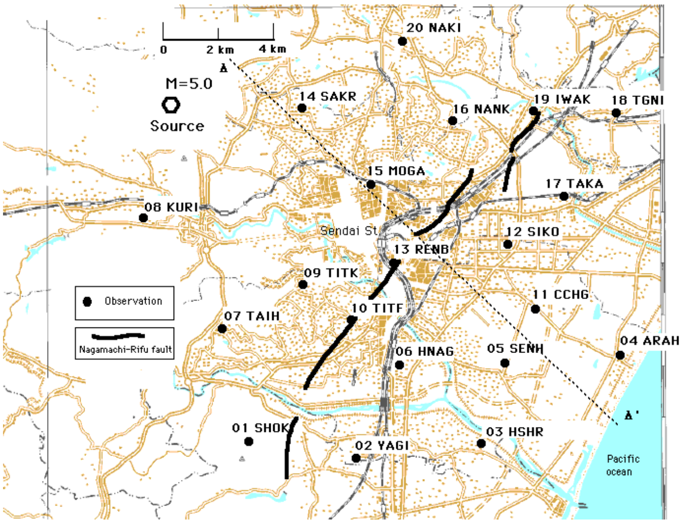


Figure 1: Observation site layout

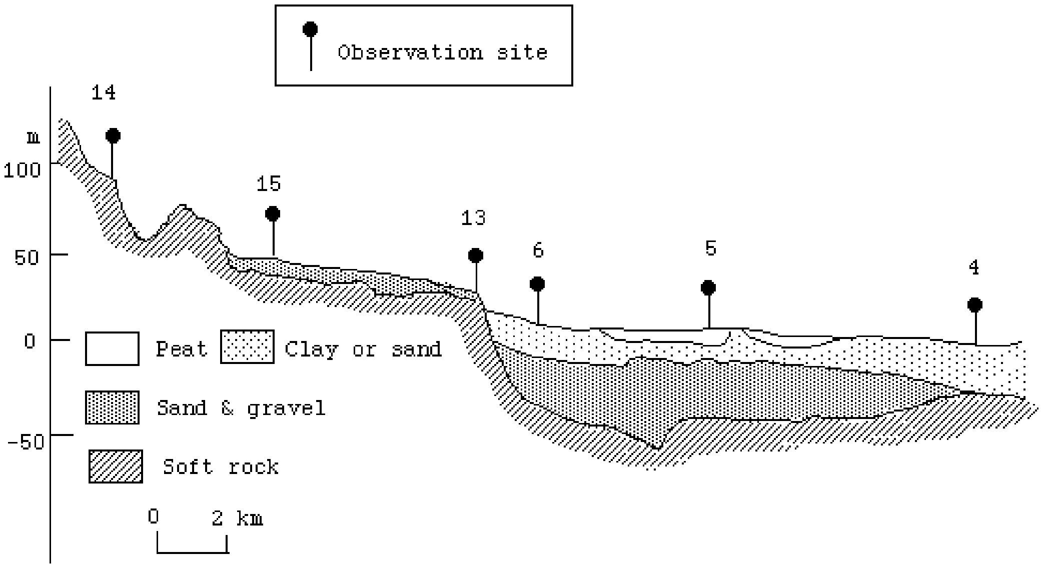


Figure 2: Typical geologic profile (A-A' in Fig. 1)

EXAMPLE OF OBSERVATION RECORDS

Test observation by Small-Titan started in June 1998 and it has been accumulating records for several earthquakes. The most significant is the records resulting from a near-distance earthquake which occurred at about 4:24 p.m. on September 15, 1998, with an epicenter in the northwestern part of Sendai City. This section describes the characteristic features found in the observed records. According to a flash report from the Japan Meteorological Agency (JMA), the earthquake's factors are as follows:.

Time and date: about 16:24, September 15, 1998

Epicenter: southern part of Miyagi Prefecture, Latitude 38.3 degree N, longitude 140.8 degree E

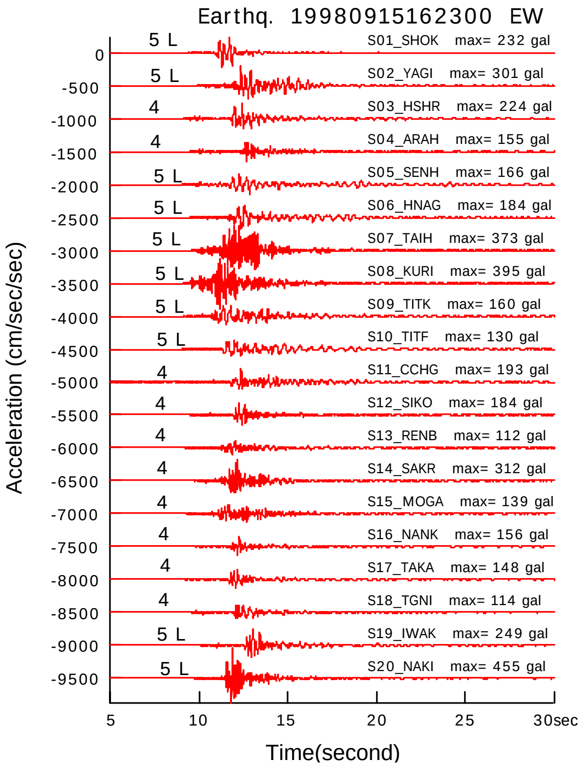
Depth of seismic focus: 10 km

Magnitude: 5.0

The epicenter is plotted in Figure 1. The earthquake registered 4 on the Japanese intensity scale of 7 in the central part of Sendai City. In response to its intensity scale, light damages such as fractures of windows, cracks of building walls and toppling or falling over of things occurred.

As shown in Figure 1, the epicenter is located extremely near some observation sites. Since the 1995 Great Hanshin Earthquake, the concerns over near-source earthquakes related to active faults have increased in Japan. In light of such an importance of near-source earthquake, the strong-motion records here are expected to represent valuable information because they were obtained by the typical array system. We made various analyses to the records: Fourier spectrum analysis, spectral ratio analysis, non-stationary spectrum analysis and so on.

Figure 3 shows the acceleration records of the E-W component obtained at individual observation sites. In Figure 3, the maximum values of acceleration are also attached together with the intensity scale measured by the records. The acceleration records in the U-D direction are similarly shown in Figure 4.



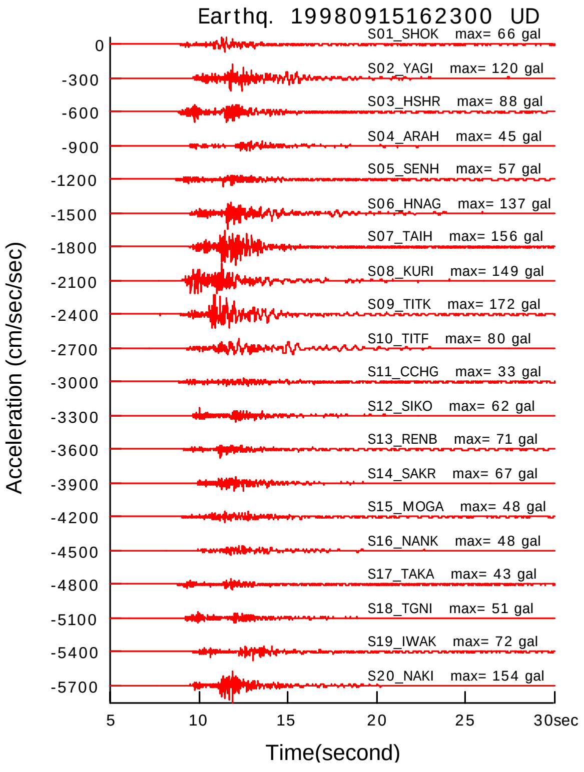


Figure 3: Acceleration record (E-W component)

Figure 4: Acceleration record (U-D component)

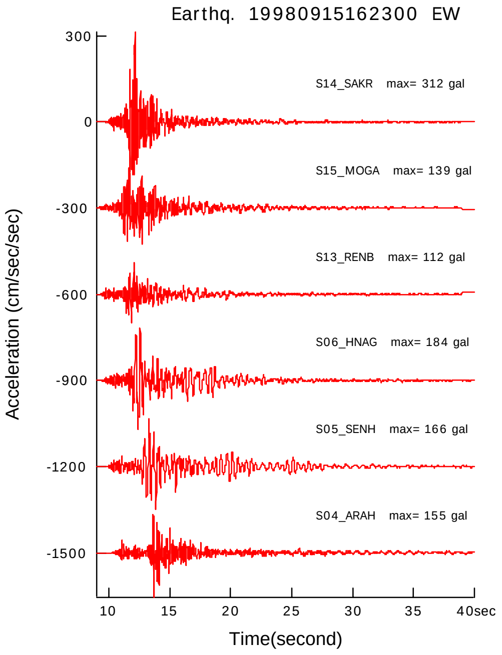


Figure 5: Acceleration records along a cross section of ground

Figures 6 and 7 show the Fourier spectra of representative observation sites for the E-W and U-D components, respectively. As seen in these charts, there are significant variations of spectral features in which the effects of soil characteristics at each site are reflected. In addition to such site-dependent features, it is clear in these spectra that short-period motions are generally predominant because of the rather small size of the source.

Figure 8 displays a motion orbit of acceleration drawn in the horizontal plane. In Figure 8, the motion orbits at each observation site are mapped with regard to the epicenter. It is clear in Figure 8 that each observation site has a tendency to show an orbit polarized in the direction toward the epicenter, suggesting the radiation pattern peculiar to the earthquake. This indicates that strong motions at the near-filed are greatly affected by the faulting mechanism. Even though being such a general tendency of the orbit, a detailed look at Figure 8 shows that there exists a difference in the degree of polarization between both sides in the east and in the west across the Nagamachi-Rifu Fault. In general, the east-side has a lower degree of polarization in comparison with the west-side. This may be attributed to the geological difference between both sides. It is thus pointed out that the source effect is weakened by the local site conditions, in particular the localized soft soils belonging to the alluvial deposit.

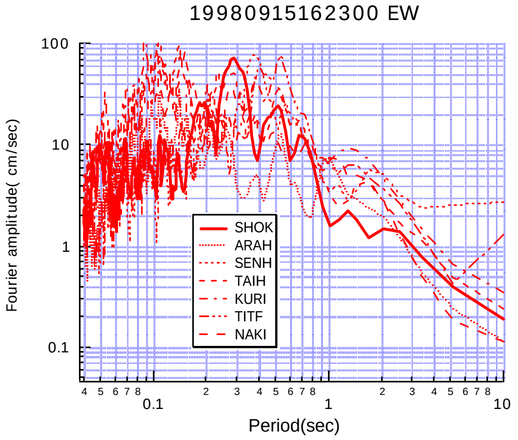


Figure 6: Fourier spectra of typical observation sites (E-W component)

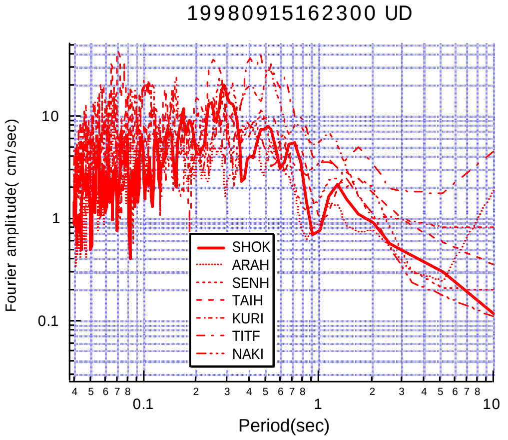


Figure 7: Fourier spectra of typical observation sites (U-D component).

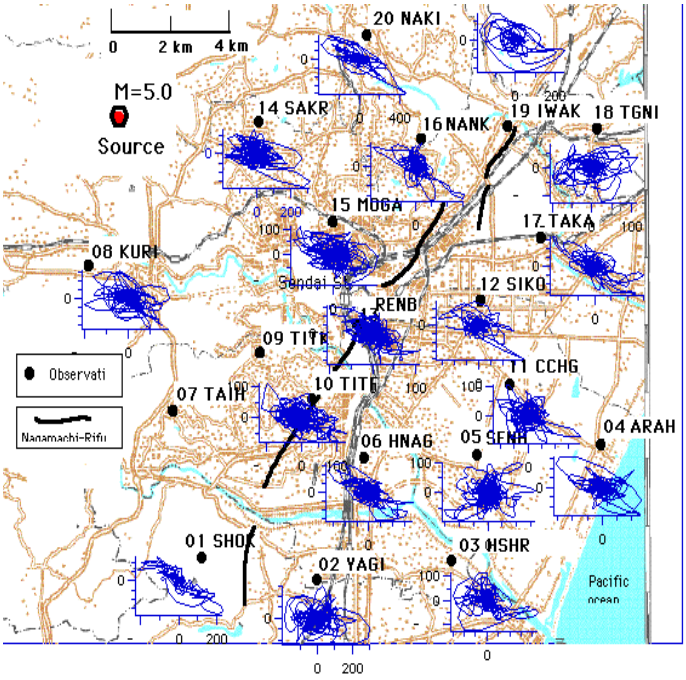


Figure 8: Acceleration motion orbits in the horizontal plane

Figures 9 to 12 show the non-stationary spectra obtained from the E-W component at representative observation sites. The non-stationary spectrum here makes it possible to analyze how the spectral amplitudes depend on period and time [Kamiyama, 1979]. We can see from these non-stationary spectra both effects of source and local site conditions. For one thing, it is interpreted from the non-stationary spectra at the near-source sites such as No.7 and No.8 that the faulting of the source happened accompanying mainly two shocks because there are clearly two contour's peaks localized in different times. As opposed to such a timely localized peaks of contour at site No.7 and No.8, the No.20 site show little localization of contour's peaks in time although it has an epicentral distance similar to No.7 and No.8. Rather than being localized with the passage of time, the contour's peak for the non-stationary spectrum of site No.20 concentrates at one instance. In correspondence with this concentration, No.20 site shows the maximum value of acceleration among all the observation sites as described above. These facts based on the non-stationary spectral analysis and peak value analysis suggests a strong directivity of source such that the faulting occurred propagating toward the direction of site No.20 and away from the side in sites No.7 and No.8. It is well known that sites situated in the direction of rupture propagation have larger amplitude with shorter duration while sites in the opposite direction have smaller amplitude and longer duration. This is the so-called "Doppler Effect." Namely, it is concluded that the Doppler effect caused the characteristic features of non-stationary spectra as shown in Figures 9 to 11. On the other hand, the non-stationary spectrum of site No.5, which is located far from the epicenter and on soft soils, shows considerably different features from sites No.7, No.8 and No.20. It has a longer predominant period of around 0.4sec than the three sites near the epicenter. This longer predominant period is clearly due to the local soil conditions. In addition to the longer predominant period, site No.5 has lengthened later phases following the main motions that are characterized as the S wave. In the non-stationary spectra for the later phases, we can recognize slightly the dispersion character of propagation, indicating that they are surface waves. This indication is also confirmed in Figure 5 so that such sites as No.6, No.5 and No.4 have later phases clearly propagating in the horizontal direction from site No.6 to site No.4. Therefore these facts suggest that surface waves were secondarily generated due to the drastic change of geology around the Ngamachi-Rifu Fault. It has been recently established that such a secondary surface wave, called the "basin-edge effect wave" [Kawase, 1996] plays an important role in determining strong motions. This time's earthquake was rather small one with a magnitude of 5.0, so the main motions composed of S wave did not have long duration enough to overlap with the later phases. However, it were of much larger size, there would have been a possibility that the S wave motions overlapped with the later phases due to the secondary surface waves with complicated interference, leading to enormous damage.

Although detailed analyses of these records are still under way, the above brief summary is enough to show that Small-Titan is an effective observation system. It is qualitatively proved in this paper that it is capable of obtaining useful information in earthquake engineering. For example, seismic intensity in local areas, local site effects, laterally inhomogeneous effects of soils and source effects related to various kinds of faulting are expected to be further clarified by its continued observation. In addition, it might provide meaningful information of input motions available to earthquake-resistant design, aimed at setting in terms of local soil conditions.

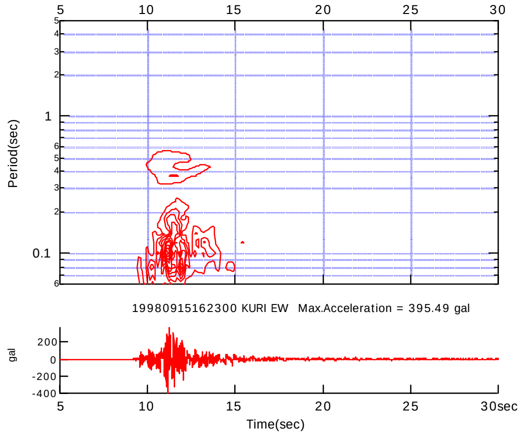


Figure 9: Non-stationary spectrum of observation site 8 (E-W component)

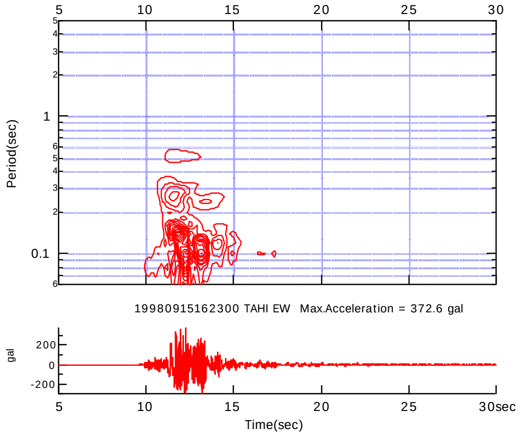


Figure 10: Non-stationary spectrum of observation site 7 (E-W component)

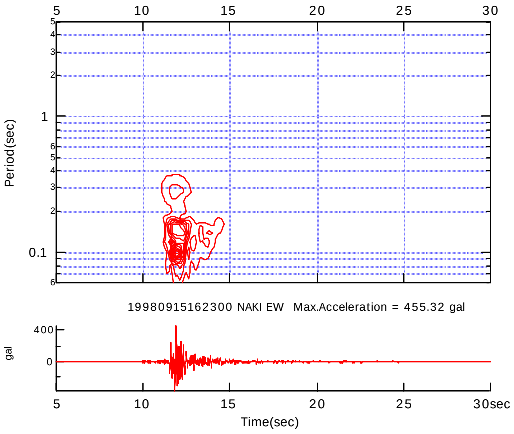


Figure 11: Non-stationary spectrum of observation site 20 (E-W component)

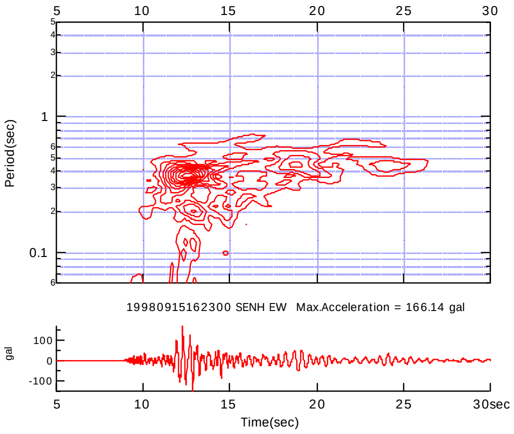


Figure 12: Non-stationary spectrum of observation site 5 (E-W component)

CONCLUSIONS

This paper has described the outline of Small-Titan and presented an example of records observed by the system. This paper placed emphasis on showing the system’s effectiveness by preliminary analyses of the records. The concluding remarks are summarized as follows:

Local soil conditions determine the spectral characteristics of strong motions more effectively than earthquake source effects. On the other hand, source effect, especially the directivity effect of faulting contributes strongly to the maximum amplitude of time history. The lateral inhomogeneity of local soils also affects strong-motion characteristics so that its existence produces some secondary waves characterized by surface waves.

REFERENCES

1. Iwan, W. D. (1979), The deployment of strong-motion earthquake instrument arrays, *Earthquake Engineering and Structural Dynamics*, Vol.7, pp413-426.

2. Kamiyama, M. (1979), Non-stationary characteristics and wave interpretation of strong ground motions, *Proc. of Japanese Society of Civil Engineering.*, No.284, pp35-48(in Japanese).

3. Kawase H. (1996), The cause of the damage belt in Kobe; ”The Basin-edge effect”, constractive interference of the direct S-wave with the basin-induced diffracted/Rayleigh waves, *Seism. Res. Lett.*, Vol.67 , pp25-34.

4. Kinoshita S. (1998), Kyoshin net (K-NET), *Seism. Res. Lett.*, Vol.69 , pp309-331.