Original Research Article

A Practical Prediction Methods of Major Earthquakes using High-frequency Tremor Events

Abstract

The earthquake prediction, one of the most efficient methods has been tried to develop based on modern scientific method this half century using seismic activity, crustal deformation, chemical anomalies without practical results except only two rare cases with the result of general pessimistic evaluation. The seismic activity has been the field of the most often approached in comparison with other phenomena. Especially foreshocks are investigated enough to provide many useful results but critical defects of unstable occurrence. On the other hands important progress is attained in the laboratory investigation of process of nucleation providing important results. However, those result cannot be confirmed by field observation just before occurrence of major earthquakes. Here we make a special seismic catalog of high frequency tremors deduced anew from continuous seismic data of just before major earthquakes using the extensive network, High-net of Japan. Analyses of catalog for three major and one a little bit smaller earthquakes show that there are three successive precursory phenomena, first at some six weeks, second at some four weeks, and finally immediately before the earthquake. And the three items of prediction, time, location and magnitude can be predicted exactly enough for actual disaster mitigation efforts at each moment of distinguishing of those precursors.

1. Introduction

Investigations on the earthquake prediction has been conducted in various fields of seismic activity, crustal deformation, ground water, electromagnetic phenomena etc., and in various time range, immediate, short and long-terms (e.g., Rikitake,1987). Concerning to the difficulty of the prediction IASPEI (1991) published guidelines to make the prediction research to be more consistent and fruitful. Yoshida and Furuya (2015) analyzed the prediction research in Japan to conclude that the reason is nothing but a large extent of diversity of individual results of anomalous phenomena. However, there are only two successful results of earthquake prediction, at the Haicheng earthquake (Wu et al., 1976) and the 1978 Oaxaca earthquake (Ohtake et al., 1977,1981). We had no new samples of successful prediction in these more than half a century with the result of general pessimistic evaluation to the earthquake prediction (e.g., Geller, 1991).

We have found that electromagnetic pulses of some 400Hz occur from a week before the

2011 Tohoku earthquake to indicate the method can be used for the immediate prediction (Fujinawa *et al*., 2013、Fujinawa and Noda、2020). But the observation network is not yet built to wait the chance in future. On the other hand, the foreshock has been well studied as possible anomalies of short- term prediction (e.g., Jones and Molnar, 1979; Scholz, 2002; Yoshida and Furuya, 2015; Tamaribuchi *et al.,* 2018). So that we focused to high frequency tremors and the small- scale micro-earthquakes (HFTs) out of the official seismic catalog. We aim to issue alarming by real-time monitoring of important parameters of HFTs observed by extensive seismic network, Hi-net in Japan, using deterministic method.

We determined to use the data base of the Hi-net seismic observation network of National Research Institute for Earth Science and Disaster Resilience (NIED) which was developed to be used for development of methods of earthquake prediction. The Hi-net is consisting of some 880 observation points spaced about 20km in whole Japan (Okada *et al*.,2004) to study seismic activities to find region of low activity before major earthquakes as the case of the Oxaca earthquake (Ohtake *et al*., 1971). The data base started to be used from April 2002 and contributing greatly to the community of earthquake prediction investigation and early earthquake warning in the world.

For example, the Hi-net data have been used to monitor asperities of the great Tokai earthquake (Matsumura, 2007). Kato *et al*. (2016) relocated small earthquakes which are masked by many small aftershocks of the large foreshock of M6.5 by using the double-difference relocation algorithm to know dynamical connection of the pre-shock to the main shock. Especially, Obara *et al*. (2004) found the low frequency tremor associated with slow slip of the descending ocean plate by analyzing original continuous data. The phenomena have been monitored for long term and short-term prediction （Obara *et al*., 2004; Obara and Kato,2016; Kubo and Nishikawa, (2020). Kato and Obara (2012) found, for instance, two sequences of the slow slip events migrating toward the mainshock rupture initiation point before the 2011 Tohoku earthquake, but without results leading to practical short- term predictions.

We tried to check whole seismic events and non-volcanic tremors in the raw continuous record to make a catalog of special seismic events to be used for short term prediction. Each member of those catalog is analyzed to check if there are any anomalous activities in accord with essential characteristics of the foreshock found previously (Jones and Molnar, 1975; Scholz 2002; Mogi, 1985), and how to get information to be used for the short-term prediction of major earthquakes.

2. Method

1)Preparatory catalog

Original continuous data are downloaded from the Hi-net data base of NIED. At first, we tried to check the case of the 2011 Tohoku earthquake and selected seismic sites in the north-eastern district of the Ibaraki prefecture where we observed the electromagnetic pulse by special antenna (Fujinawa and Noda, 2015, 2019). The area including the site KAMIS where crustal deformation was detected at the time of the 2011 Tohoku earthquake. We started to check by eye the 100-trace continuous waveform images of every hour at several sites for substantial length of time. It is assumed to focus HFTs based on own experience to have detected the electromagnetic pulse of some 400Hz (Fujinawa and Noda, 2015, 2019). Meanwhile, we can find several kinds of candidate tremor events appeared significantly often just before this great earthquake.

The characteristics of the tremor events are quantized to develop automatic program to detect those events for the special catalog. The program are several times revised through checking the result by trial and error. The earthquakes contained in the official catalog of NIED and JMA (Japan Meteorological Agency) are not included in the special catalog. At first, we selected four kinds of possible candidate of small micro-earthquake and tremor events. Characteristics of the first version of the selection are as followings in terms of duration time, strength, and dominant frequency,

ⅰ. Small micro-earthquake: too small to be included in the official catalog,

ⅱ. Microseisms: well-known tremor lasting for long hours not related with earthquake, frequency is some 0.5Hz and spectral strength of $1(\mu m/s)^2$,

ⅲ. non-volcanic tremor: continuously observed for several hours with dominant frequencies of three bands (3, 10, 40Hz)

ⅳ. Remote earthquakes: far field earthquake without or ambiguous P-wave,

Under the previous definition of the events, we checked catalog at 28 Hi-net sites in region of distance of 800km from the Aomori Prefecture northward to the Chiba Prefecture southward if there are any of anomalous events at time periods of immediate foreshock, several days before main shock. Some of events are found to have increased just before the main shock. But it is very difficult to have any simple rules or general characteristics possibly because of so many sites in so many geological conditions in the case of the 2011 great Tohoku earthquake of magnitude Mw =9.0.

2) high frequency tremor

We selected anew a moderate level of major earthquake to find tremors which can be used as the immediate precursors. The 2016 Kumamoto earthquake of class M 7 was selected. Referring focal region of the Kumamoto earthquake (JMA and MRI, 2016) we assumed the area of focal region to choose 20 sites of seismic observation of Hi-net.

Several times of try and errors result in four kinds of the high frequency tremors and two kinds of small micro-earthquakes as candidates of precursory phenomena as below,

No.1: near field ultra-micro earthquake: ordinary micro-earthquake with smaller strength than those included in the official catalog. P-wave and S-wave are both clear, frequency band is (2~30Hz), and peak frequency (2~20Hz),

No.2: remote field small micro earthquake: ordinary micro-earthquake with smaller strength than those taken in the official catalog. S-wave are clear, but P wave is not clear because of dissipation, frequency band (7~20Hz), peak frequency(6~15Hz),

No.3: near field high frequency tremor like string: S-wave is clear, but P wave is not clear. Laps time is about 15s, relatively long, frequency band (2~40Hz), peak frequency (3~20Hz),

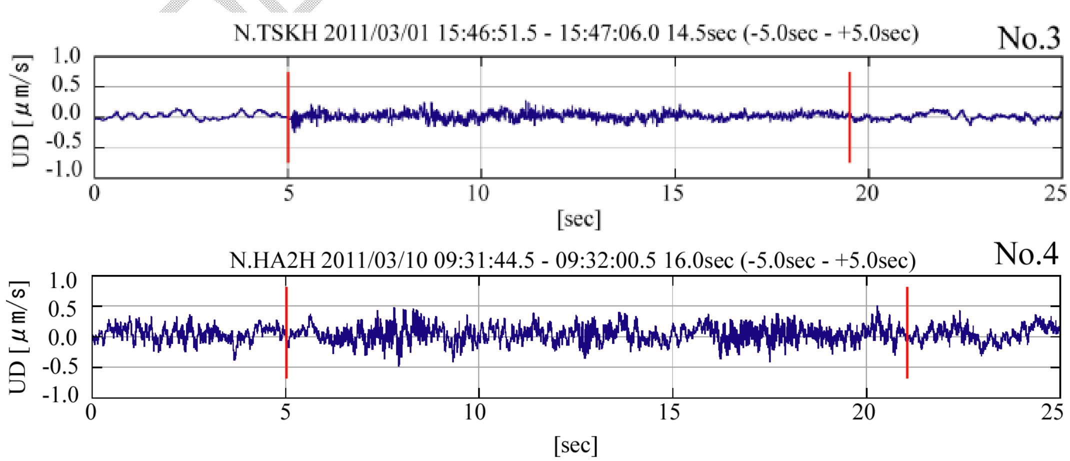
No.4: near field high frequency tremor (like a swarm): S-wave are clear, but P wave is not clear. smallest variations of amplitude, frequency band (2~20Hz), peak frequency (3~20Hz).

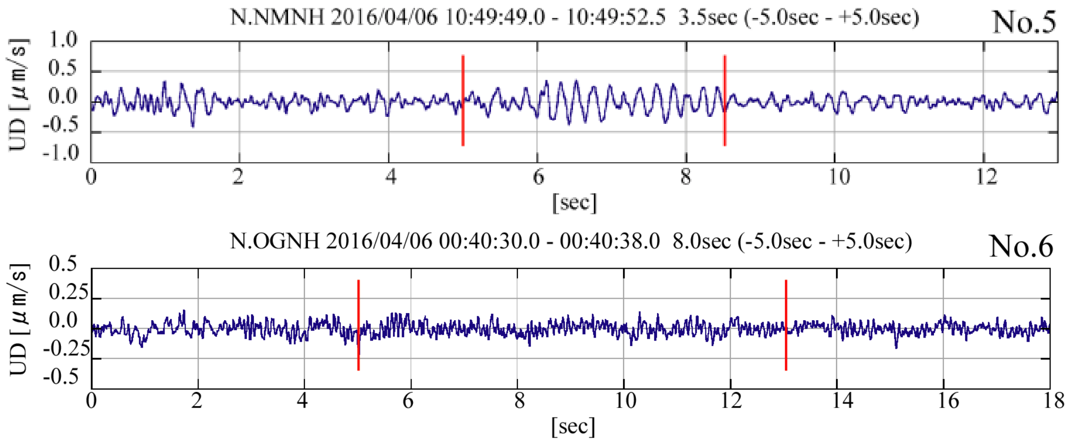
No.5. Far field high frequency tremor: high frequency components are dissipated, and low frequency components are clear, lapse times are relatively long of some 15s, frequency band (2~15Hz), peak frequency (4~5Hz),

No.6 Combined high frequency tremor: a modification of the event No.3, lapse times are longest (~30s), smallest variations of amplitude.

Those four kinds of selected tremors are shown in Fig. 1.

Fig.1 Waveforms of HTMs, No.3~No.6.



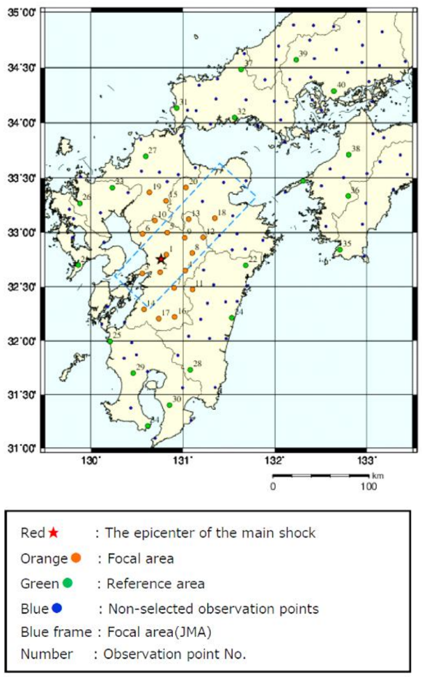


3) Selection of area

Three major earthquakes, the 2016 Kumamoto earthquake (Mw 7.0), the 2007 Niigata off Chuetsu earthquake (Mw 6.6) and the Iwate-Miyagi Nairiku Earthquake in 2008 (Mw 6.9) and a little bit small Iburi earthquake in 2018 (Mw 6.6) are taken as samples. At first, hourly number of each event is calculated. Observation sites are selected in the focal region referring JMA and MRI (2016, 2007, 2008, 2018). As to the Kumamoto earthquake there are no earthquakes as foreshock of magnitude larger than 2.0 from January 1 to April 14,2016 when the largest foreshock of Mw 6.2 occurred. And the Niigata off Chuetsu earthquake was preceded only by one microearthquake of M2.2 in mid-June and one microearthquake of M1.8 in early July (JMA and MRI, 2016), and the Iwate-Miyagi Nairiku earthquake only by two microearthquake of M1.6 before 32 and 42 minutes before major earthquakes. So that there are almost no foreshocks before three major earthquakes if we assume the foreshock of Kumamoto with magnitude 6.2 and the main shock are considered as one chain of seismic activity.

In the case of the Kumamoto earthquake 20 sites are selected mostly in Kumamoto prefecture around focal region, and another 20 sites are selected in the reference region including 10 prefectures (Figure 2).

Fig.2 Seismic observation sites of evaluation area and the reference area for the case of the Kumamoto Earthquake .Each area have 20 sites.



	code	Station name	Prefecture	Excavation [m]	Epicentral distance[km]
Vicinity observation points" focal area"	N.MSIH	MASHIKI	Kumamot	255	7.3
	N.TYNH	TOYONO	Kumamot	113	13.2
	N.MSMH	MISUMI	Kumamot	303	23.9
	N.YABH	YABE	Kumamot	106	27.2
	N.KKCH	KIKUCHI	Kumamot	203	27.9
	N.TMNH	TAMANA	Kumamot	103	32.0
	N.IZMH	IZUMI	Kumamot	103	32.1
	N.HKSH	HAKUSUI	Kumamot	114	32.4
	N.ASVH	ASO	Kumamot	130	32.7
	N.KHKH	KAHOKU	Kumamot	103	39.9
	N.SBAH	SHIIBA	Miyazaki	203	44.5
	N.NMNH	NAMINO	Kumamot	103	48.5
	N.OGNH	OGUNI	Kumamot	126	49.7
	N.ASKH	ASHIKITA	Kumamot	303	54.0
	N.UKHH	UKIHA	Fukuoka	203	59.6
	N.UWEH	UE	Kumamot	180	60.7
	N.HYOH	HITOYOSHI	Kumamot	126	60.8
	N.SNIH	SHONAI	Oita	232	68.9
	N.TARH	TACHIARAI	Fukuoka	440	69.1
	N.YGNH	YAMAKUNI	Oita	203	77.3
Distant observation points" reference"	N.NGSH	NAGASAKI	Nagasaki	203	84.5
	N.KIGH	KITAGAWA	Miyazaki	213	86.6
	N.FJIH	FUJI	Saga	106	88.0
	N.KWMH	KAWAMINAMI	Miyazaki	216	93.9
	N.AKNH	AKUNE	Kagoshima	205	99.0
	N.IMRH	IMARI	Saga	105	100.1
	N.WKMH	WAKAMIYA	Fukuoka	102	105.7
	N.MJSH	MIYAKONOJO-S	Miyazaki	120	117.3
	N.KORH	KORIYAMA	Kagoshima	206	120.4
	N.KYAH	KANOYA	Kagoshima	104	150.3
	N.TYUH	TOYOURA	Yamaguchi	203	154.0
	N.HOFH	HOFU	Yamaguchi	203	161.9
	N.IKTH	IKATA	Ehime	153	164.8
	N.YKWH	YAMAGAWA	Kagoshima	206	172.0
	N.OOTH	OTSUKI	Kochi	102	182.4
	N.HIYH	HIYOSHI	Ehime	203	200.8
	N.MTMH	MUTSUMI	Yamaguchi	203	208.2
	N.TBEH	TOBE	Ehime	137	217.9
	N.TGUH	TOGOUCHI	Hiroshima	105	243.5
	N.KURH	KURE	Hiroshima	104	243.8

In the process of analysis of the Kumamoto earthquake we noticed that there might be spurious effect of the aftershock after the large foreshock. So that we determined that analysis is from the very start of evaluation to the foreshock not to the mainshock in accord with the general treatment (Jones and Molnar,1979; Yoshida and Furuya, 2015; Maeda, 1999) that the big foreshock occurred before short time interval compared with the several days is taken as belonging to a same chain of one seismic activity.

Observation sites for the evaluation area are selected around epicenter with the condition that whole sites have epicentral distances less than a fixed value, 77km in case of Kumamoto earthquake (Fig. 2). Observation sites for reference area are selected at points with epicentral distance less than 100km, and sites of the reference area are selected in the belt-shaped area of epicentral distance from 100km~200km. For the Niigata Chuetsu earthquake selected sites in the focal area are largely in Niigata prefecture except four sites. And the 20 sites in the reference area are selected in surrounding prefectures. Data length of each case is two months in this work.

4) General feature of activities of HFTs

Table 1 shows comparison of total number of each high-frequency tremor in the focal area of the Kumamoto earthquake during a month at 20 sites.

Table 1 :Number of each kind of the high frequency tremor events during the sampled time-period of March 15~April 16 before the Kumamoto earthquake. Data written by bold style indicate they are two largest events at each observation site. There are large differences of occurrence number between sites amounting some 30 times, and between kind of events some 100 times.

Observation Site		Total	kind of events					
No.	Name	Number of events	1.near field SME	2.remote field SME	3.near field HFT like string	4. near field HFT like swarm	5.far field HFT	6.compound HFT
1	Mashiki	31,347	1,105	**1,808**	103	194	**26,727**	1,410
2	Toyono	17,696	1,047	879	1,733	**2,208**	**10,576**	1,253
3	Misumi	2,841	**1,164**	279	137	212	**874**	175
4	Yabe	1,053	**310**	57	91	**291**	251	53
5	Kikuchi	7,236	**1,970**	180	**2,249**	1,684	886	267
6	Tamana	8,777	1,781	240	**2,648**	1,443	**1,949**	716
7	Izumi	1,410	**322**	16	212	269	**504**	87
8	Hakusui	10,399	620	522	**1,664**	1,011	**5,921**	661
9	Aso	26,372	228	345	509	**4,212**	**19,508**	1,570
10	Yamagashi	26,188	**6,175**	768	**8,442**	5,542	3,550	1,711
11	Shiiba	462	73	19	66	**102**	**168**	34
12	Namino	26,307	792	865	927	**5,396**	**15,858**	2,469
13	Oguni	18,858	906	191	1,197	**13,091**	**2,230**	1,243
14	Ashikita	3,779	**2,021**	45	298	470	**852**	93
15	Ukiha	968	**292**	52	**283**	132	126	83
16	Kami	12,392	**4,769**	511	1,750	1,081	**3,913**	368
17	Hitoyoshi	21,831	1,326	246	3,199	**11,386**	**3,858**	1,816
18	Shounai	6,631	**621**	460	249	153	**4,919**	229
19	Tachiarai	1,356	**217**	118	87	46	**828**	60
20	Yamakuni	1,679	**580**	115	69	89	**616**	210
		sum for 20 sites	26,319	7,716	25,913	**49,012**	**104,114**	14,508
		cases of top 2	11			6	16	

"Total" means sum of whole events from No.1 to No.6, "event" means the total number of each tremor observed in a month. Activities scatter greatly among 20 sites. And, it is noticed that number of event No.5 is first or second in almost all 16 sites of total 20 sites, and near field micro-earthquake No.1 is first or second at 11 of total 20 sites.

5) Definition of anomalous activities and score

We selected the hourly number of each event as fundamental quantity in the analysis. And three days running mean of the hourly data are adopted to reduce environmental noises. The filtered data are sampled at each 12 hours denoted by $x_{ij}(t)$ at observation site *i* of event *j*. The threshold value NC_{ij} to discriminate anomalously active time is defined using mean M_{ij} and standard deviation σ_{ij} of $x_{ij}(t)$ during a month before earthquake occurrence as,

$$NC_{ij} = M_{ij} + 1.3 * \sigma_{ij} \tag{1}$$

If the observed value $x_{ij}(t)$ at time *t* exceeds the critical threshold NC_{ij} the score value $SC_{ij}(t)$ is defined as below,

$$SC_{ij}(t) = 1\,, x_{ij}(t) > NC_{ij} \tag{2a}$$

$$SC_{ij}(t) = 0\,, x_{ij}(t) \leq NC_{ij} \tag{2b}$$

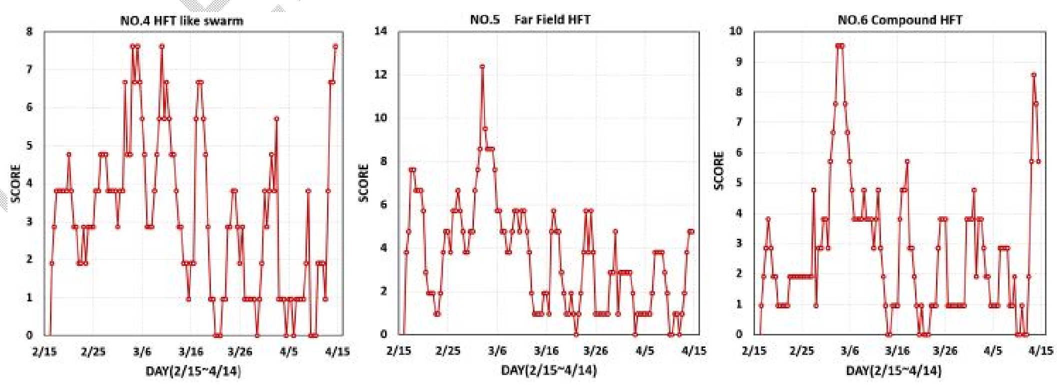
The score shows the degree of activity of the events *j* at site *i* and at time *t* in the evaluation area as the focal area of sample earthquake. The score is introduced to count number of sites where the activity exceeds local threshold value. The score value at time *t* summed in any area is called "total score", which is similar to the number of patches exceeding a critical radius (Dietrich, 1986), indicating number of sites where anomalous activity is detected.

3. Result

1) candidate of precursory phenomena

Fig 3 shows a sample of time series of total score of essential three HFTs events No.4, No.5 and No.6 during two months before the Kumamoto earthquake every 12 hours in the focal area.

Fig. 3 Typical time change of the total score of three essential frequency tremors No.4~No.6 for two months before the Kumamoto earthquake. The total sore for any HFTs means total number of seismic observation sites where any events are in the state of anomalous activity. The event No.6 has the largest and isolated peak with the sharpest increase of score just before the Kumamoto major earthquake at 21:00 JST on ,14, April.2016.



At first the second largest peak of score 9 of the event No.6 is very impressive at afternoon on 13, April just before the M7.2 major earthquake (foreshock). The earthquake occurred at

22:13, on April 14 suggesting that the largest peak is to be related with immediate precursory phenomena referring the foreshock activities just before the earthquake (Jones and Molnar, 1979). The largest peak appeared on March 3, and assumed to be the initial precursor. And, the third largest peak of the event No.6 appeared on March 18 and assumed to be intermediate precursor as third essential events. The events No.4 and No.5 have more or less similar peaks at those three times.

Previous studies on foreshock (Jones and Molnar,1979; Das and Sholz, 1981; Scholz, 2002) show time rate of ocurrence of the foreshock increase greatly just before the earthquake following inverse of time *t*, (1/*t*) and accelaration increase obeying the general rupture law. Referring these finding and general rupture law (Fukuzono, 1985; Voight 1989) we suspect that these three dominant peaks at about 1 week, 4 weeks and 6 weeks are candiate of the immediate, intermediate initial precursors.

The scores are defined for each event themselves, and also for combination of 2 or 3 of events with the result of 17 kinds of prediction index. The score of combined events are normalized by number of group events in order to be compared with each other.

2) Distinguishing precursors

There are another large peaks in the early stage as seen in Figure 3 besides the largest three peaks as precursors before the major Kumamoto earthquake. These peaks may be influenced by the daily and weekly environmental noises. Anyhow we must distinguish those peaks from the real peaks related to any stage of nucleation process to issue alarming correctly and in due times. We checked these peaks introducing two key parameters, peak strength (number of score) and time rate of them (acceleration) for each event and combined events referring the general rupture law (Fukuzono, 1985; Voight, 1987, Jones and Molnar(1979), and Scholz (2002)).

And those threshold parameters are used to make the distinguishing table. The table is consisting of peak time, maximum score peak, and the acceleration for every simple and combined event as seen in Table 2-1, 2-2.

Table 2-1：Kumamoto Earthquake

Results of examination of the second largest peak of whole events in the focal area at the first period Pe.1. It is shown that there is no event except No.4 exceeding the criteria of the imminent alarming. Moreover, the most important event No.6 does not exceed the criteria with the result that the peak is not recognized as a precursor of immediately before the major earthquake at the period 12. However, the case exceeds another criteria of short term precursor defined as 1) more than 53% events have larger score than 4. 5 and 2) events No.4 or No.5 exceeds maximum score of 7, and the maximum increasing speed exceeds 8 score/day.

Table 2-1

Kumamoto EQ		(a) Focal Area											
		Initial Prec.			intermediate Prec.			calm Pe.(sample)			immediate Prec.		
disting. result		O			O			X			O		
event		Feb.29			March .15			March. 30			April(10)		
		Pe4		94%	Pe7		88%	Pe10		6%	Pe12		94%
No.	name	day	max score	max. veloci.	day	max score	max. veloci.	day	max score	max. veloci.	day	max score	max. veloci.
1	N. field small Mi.Ea.	19.5	4.8	3.8							60.5	4.8	3.8
2	F.field small Mi.Ea.	18.5	7.6	3.8	33.0	4.8	3.8	46.5	4.8	5.7	59.0	5.7	5.7
3	N.field HFT(swarm t.)	19.0	6.7	5.7	32.5	7.6	5.7				59.5	5.7	3.8
4	N. field HFT(string t.)	19.0	7.6	5.7	32.5	6.7	7.6	48.5	5.7	3.8	60.5	7.6	5.7
5	F.field HFT	18.0	12.4	7.6	32.5	5.7	7.6	45.0	4.8	3.8	60.0	4.8	3.8
6	Compund t. HFT	18.5	9.5	5.7	33.0	5.7	5.7	47.0	4.8	5.7	59.5	8.6	7.6

Kumamoto EQ		(b) Reference Area											
		Initial Prec.			intermediate Prec.			calm Pe.(sample)			immediate Prec.		
disting. result		X			X			X			X		
event		Feb.29			March .15			March. 30			April(10)		
		Pe4		88%	Pe7		6%	Pe10		76%	Pe12		82%
No.	name	day	max score	max. veloci.	day	max score	max. veloci.	day	max score	max. veloci.	day	max score	max. veloci.
1	N. field small Mi.Ea.	19.5	4.8	1.9	32.0	4.8	3.8				60.5	4.8	5.7
2	F.field small Mi.Ea.	19.0	5.7	3.8	33.0	5.7	7.6				60.5	4.8	3.8
3	N.field HFT(swarm t.)	19.0	4.8	3.8	31.5	4.8	3.8	45.5	6.7	5.7			
4	N. field HFT(string t.)	17.5	4.8	3.8	33.0	4.8	3.8	45.5	7.6	5.7	60.5	5.7	5.7
5	F.field HFT	18.0	7.6	5.7	31.5	6.7	7.6						
6	Compund t. HFT	18.5	6.7	3.8							60.5	6.7	3.8

Table 2-2

Niigata EQ.		(a) Focal Area											
		Initial Prec.			intermediate Prec.			calm Pe.(sample)			immediate Prec.		
disting. result		O			O			X			O		
event		May. 22			Jun. 21			July. 1			July. 11		
		Pe2		100%	Pe2		100%	Pe4		12%	Pe6		88%
No.	name	day	max score	max. veloci.	day	max score	max. veloci.	day	max score	max. veloci.	day	max score	max. veloci.
1	N. field small Mi.Ea.	9.0	4.8	5.7	28.5	5.7	3.8						
2	F.field small Mi.Ea.	7.0	8.6	5.7	27.0	6.7	1.9				55.5	4.8	5.7
3	N.field HFT(swarm t.)	6.0	4.8	3.8	25.0	5.7	3.8				56.0	4.8	3.8
4	N. field HFT(string t.)	8.5	4.8	1.9	27.5	4.8	5.7	45.5	4.8	3.8	56.0	6.7	5.7
5	F.field HFT	8.0	11.4	6.0	29.5	6.7	5.7				56.5	5.7	3.8
6	Compund t. HFT	7.0	8.6	3.8	27.5	4.8	3.8				56.0	9.5	13.3

Niigata EQ.		(b) Reference Area											
		Initial Prec.			intermediate Prec.			calm Pe.(sample)			immediate Prec.		
disting. result		X			X			X			X		
event		Jun. 21			21-Jun			1-Jul			July. 11		
		Pe2		100%	Pe6		100%	Pe10		12%	Pe12		29%
No.	name	day	max score	max. veloci.	day	max score	max. veloci.	day	max score	max. veloci.	day	max score	max. veloci.
1	N. field small Mi.Ea.	8.0	4.0	2.0	28.5	5.0	4.0						
2	F.field small Mi.Ea.	6.5	7.0	2.0	29.0	7.0	4.0						
3	N.field HFT(swarm t.)	8.0	6.0	4.0	28.0	7.0	4.0						
4	N. field HFT(string t.)	7.5	9.0	6.0	28.0	8.0	6.0	49.0	4.8	5.7			
5	F.field HFT	7.5	6.0	4.0	27.5	6.0	6.0						
6	Compund t. HFT	7.5	8.0	4.0	28.0	7.0	4.0						

In order to distinguish three largest peaks during each period of five days, the two months are divided into 12 periods (Pe.). The threshold values of distinguishing are determined under the condition that each candidate precursor is to be appeared in due order in evaluation region but not in the reference region at any period. Those conditions are checked at six area, three focal area and for three reference area of the three sample earthquakes. In addition there must be 70% events with score larger than 4 in whole 17 individual and multiple (2 or 3) events for enough degree of confidence~~(under the beginning date of the period)~~ . We found that the immediate precursor can be discriminated from intermediate and initial precursor. The resultant threshold values are named as the distinguishing table.

3) Distinguishing results

3)-1 Kumamoto earthquake

Results of distinguishing of three largest peaks for the data of two months using total scores and its time derivative (acceleration) for the evaluation (a) and the reference areas (b) are shown in Table 2-1. There included only 4 periods, three periods concerning the three kinds of precursory activities (Initial, Intermediate, immediate Pre. in the Table 2-1) and one for example of calm state (Pe.10, calm Pe.) in terms sample of anomalous high activities. The initial precursor appeared at the 4th period (about 6 weeks before the earthquake), the intermediate precursor at 7th period (some 4 weeks before), and immediate precursor at 12 period (about a week before). Parameters related directly to the distinguishing are shown by using red letter in the colored field and the results are shown in the column "disting. result").

① Evaluation area (immediate precursor)

The strongest activity is distinguished at 4th period, the second largest activity at 12th period, a week before the major earthquake, and third one at 7th period. The second largest peak at 12th periof has parameter pair of (9,8) compared with threshold pair of (7,6) suggesting the peak corresponds to the immediate precursor as indicated in the column "disting. result". It means that the immediate precursor is distinguished at about 1.5 days before the large foreshock, and 2.7 days before the mainshock.

② Evaluation area (intermediate precursor)

The third largest peak appeared at the seventh period. Events No.4 and No.5 satisfy conditions for the intermediate precursor, and score of the event No.6 is smaller than 6 ,with the result that the peak is not for the immediate and initial precursors. We can assume that there will be major earthquake about 4 weeks later.

③ Evaluation area (initial precursor)

The first peak is largest in the three peaks in terms of score number. The concerning parameters satisfy the condition of the immediate precursor, but subsequent conditions concerning final threshold values of distinguishing among three events result in the initial precursor.

④ Reference area

Distinguishing result for the reference area of the Kumamoto earthquake is shown in (b) of Table 2-1. The most important point is the difference compared with the result of period 12 for the evaluation result. In this area the maximum score is smaller than the threshold value of 7.0 though acceleration satisfy the condition with the result to conclude that there is no major earthquake in this area. Event No.3 in the period 10 satisfies the distinguishing condition of immediate precursor, but No.3 is not assumed as distinguishing event for immediate precursor with the result to suggest that there may not happen any large earthquake.

And we found there are no periods satisfying the condition for neither intermediate nor initial precursors. Afterall we can assume there are major earthquake in the evaluation area based on distinguishing that three are successive precursors at some six, four weeks and one week before.

3)-2 Niigata Chuetsu earthquake

The distinguishing rule is not given beforehand at present, and need to analyze real sample of earthquake. In the case of second earthquake the first rule for the Kumamoto earthquake should be updated to work for both of two earthquakes. At first rule is applied to the second earthquake to find correction points so as the new rule is simultaneously applied to two sample earthquakes. In the case of the three earthquake the third common rule is found through the same routines.

Results of distinguishing for the Niigata earthquake is shown in Table 2-2, (a) for evaluation area and (b) for the reference area.

① Immediate precursor: The immediate precursor is distinguished at 12th period of evaluation area owing that rate of activity of whole single and combined events is 94% and convinced parameter pair is (10, 13.3) larger than the threshold value (7,6) satisfying condition for immediate precursor. We can see that the immediate precursor is distinguished on July 12, 0:00 about 4.5 days before the major earthquake occurred on July 16, 10:00.

② Intermediate and initial precursor

The intermediate precursor is distinguished at 7th period in 12 periods on the contrary to our expect. As matter of facts, the event No.4 only satisfy distinguishing conditions for the intermediate precursor, but No.4 is not principal event and event No.6 does not satisfy condition for the immediate precursor indicating that the peak is determined to be intermediate one. On the other hand the distinction quality rate is larger than 70%, and distinction conditions for intermediate precursor (maximum score >=7 and acceleration >=8/day) are satisfied with the result that the peak is determined as for the intermediate precursor. The initial precursor at period 2 is distinguished as the case of Kumamoto earthquake.

③ Reference area

Distinguishing analysis show that there are no periods to satisfy conditions for any of three precursors indicating that there are no possibility that major earthquake occurs in the reference area.

3)-3 Iwate-Miyagi Nairiku earthquake

The distinguishing rule for the case of three samples of earthquake including the third sample earthquake the Iwate-Miyagi Nairiku earthquake (2007) is made by the adjustment of the preceding rule for the case of two samples of the Kumamoto and the Niigata Chuhetu earthquakes. Results of distinguishing show that the three precursors item are stable enough to be practically used.

4) Prediction parameters

4)-1 Occurrence time

Results of distinguishing of largest three peaks of three major earthquakes are shown in Table 3.

Table 3 Occurrence of three largest score peaks, initial, intermediate, and immediate precursors and simple statistical analysis indicating that each estimation can be issued 6.4±1.2 weeks, 4.5±0.4weeks, and 0.5 ±0.3 weeks, before occurrence of major earthquakes.

Earthquake / Precursor	Kumamoto (Wk)	Niigata (Wk)	Iwate (Wk)	Mean (Wk)	Devation (Wk)
Initial	6.3	7.6	5.3	6.4	1.2
Intermediate	4.1	4.8	4.5	4.5	0.4
Immediate	0.3	0.8	0.3	0.5	0.3

Three kinds of dominant precursors, initial , intermediate, and immediate, are shown to occur in order and at 6.4 ±1.2 weeks for initial precursor, at 4.6 ±0.4 weeks for intermediate precursor, and at 0.5 ±0.3 weeks, respectively. The results indicate the HFTs are useful phenomena for predicting occurrence time of major earthquakes.

We can distinguish each precursor in real-time to predict the earthquake occurrence by using multiple precursors, step by step. The results are depending on analyses of maximum length of two months with the result of possibilities of there are another precursor earlier than two months. The possibility is not large referring that the foreshocks are reported to occur just before 1 week and some fifty days before occurrence of major earthquake (Jones and Molnar, 1979; Yoshida, 1990, Scholtz, 2002).

4)-2 Magnitude

We analyzed the temporal change of the high-frequency tremor to find noticeable activity in relation with earthquake occurrence. Here we use the spatial spreading of the detected sites, i.e. the total score every half day for the case that number of sites is 21. We used No.5 of the most sensitive events for this purpose because of largest score and detected firstly in three precursors. The score shows distribution of sites where activity is anormal.

The area of the distribution of seismic activity S is used to estimate magnitude of main shock (Utsu and Seki, 1955; Kanamori and Anderson, 1975) ,

$$M = LOG10(s) + 4 \tag{3}$$

Referring the empirical relation we assume that magnitude *M** is estimated by

$$M^{*} = LOG10(S^{*}) + C \tag{4a}$$

where *C* is a constant number to get the relation to be used for present case. Spreading area S^{*} is assumed as $S^{*} = Ps(5)^{*}20^{*}20(km^{2})$ because of the lattice span of Hi-net is some 20km

(Okada, 1985). The result is shown in table 4 for the value $C = 3.4$ with confidence accuracy of ±0.3. We can estimate magnitude with error of ±0.3.

Table 4 Magnitude prediction M compared with true values of three sample major earthquakes. The estimation uses the initial precursor by the event No.5 some 6 weeks before occurrence of the main shock with the confidence limit of. ±0.3.*

Parameter / Earthquake	Ps(5)	M*	Mj	ΔMj
Kumamoto	12.5	7.1	7.3	-0.2
Niigata	11.5	7.1	6.8	0.3
Iwate-nairiku	13.5	7.1	7.2	-0.1

The intermediate precursor has about half area smaller than other two precursor indicating that we can use formula (4a) using value of C for each precursor to get enough accurate value of general error limit of ±0.5 for practical needs of disaster mitigation.

4-3) Epicenter

The third item of the prediction of earthquake is location. In the earlier stage of development we found that the approximate center point of the detected points is near the epicenter of the earthquake within accuracy sufficient for practical effort for disaster prediction. Table 5 is results of assumed position of epicenter of the three major earthquakes determined by the initial precursor.

Table 5 Epicenter prediction results compared with true values of JMA for three sample major earthquakes. The estimation uses the total score of the event No.5 some 6 weeks before occurrence of the main shock with the result of confidence limit of±0.4 °.

Initial Precursor.

Parameter / Earthquake	Mj	No.5	Epicent. (JMA)		Epicent.(estimate)		Confidence Lim.	
		Ps(5)	E(°)	N(°)	E(°)	N(°)	E(°)	N(°)
Kumamoto	7.3	13	32.5	130.5	32.7	130.8	0.2	0.4
Niigata	6.8	11	37.6	138.7	37.2	138.8	-0.4	0.1
Iwate	7.2	14	39	140.9	39.1	140.8	0.03	-0.1

The initial precursor has largest total score of event No.5, so that here is illustrated for the initial precursor. The error are less than ±0.4° for the Kumamoto and Niigata-Chuhetsu earthquake, compared with less than 0.1° for the Iwate-Nairiku earthquake.

4. Discussion

1) Score and its velocity

Relation between number of the rate of foreshock and its acceleration is found to be generally applied in many types of rupture （Jones and Molnar,1979; Scholz,2002; Voight, 1989; Fukuzono,1985）. Just before the rupture the acceleration increases in proportion to α power of rate of activity with the following empirical relation with the result of rapid intensification of the activity,

$$d^2N/dt^2 = A^*(\frac{dN}{dt})^{\alpha} \quad (5)$$

where the parameter is known about 2 for tertial creep and deformation before landslides (Fukuzono,1982; Voight, 1989; Scholz,2002).

Here the three largest peaks are examined if the relation is consistent to the relation (5) by assuming that α=2 for the sake of small dynamic range of score. The constant A is calculated for the three events No.4, No.5, No6. Using this relation we know the average of constant A for the three events is 0.2 for the immediate precursor, 0.4 for the initial precursors , and 0.13 for the intermediate precursor. The average value for the three precursor is 0.23. This value is nearly the same as 0.18 for the foreshock (Scholz, 2002) suggesting that the HFTs are induced by rupture of the asperity on the plate boundaries.

The high-frequency tremors are understood to be induced by as rupture of asperities distributed on the plate as the foreshock is explained (e.g., Jones and Molnar,1979; Scholz, 2002). We can suppose the there are several kinds of rupture of asperities.

2) Nucleation process

Each of these precursor are suggested to occur successively as different phases in the nucleation processes (Das and Scholz, 1981; Dieterich, 1986; Ohnaka *et al*., 1986; Ohnaka, 1998; Ohnaka and Shen, 1999, Ohnaka, 2000). HFTs occur almost all time for two months having three largest peaks before major earthquake compared with foreshocks found to precede less than about several tens of percent of main shocks with considerable scattering (Jones and Molnar,1979). And there is considerable commonality of the precursors among three sample earthquakes.

Anomalous activity of HFTs supposed as precursory phenomena can be understood from the point of fault slip rupture model (Dieterich, 1985; Ohnaka1985). They propose that the slow slip starts slowly to occur from the time when the tectonic stress increase to attain the critical value inducing preceding seismic activity. Present three kinds of precursors can be explained in this model to be different subphase of the stable quasi-static phase followed by several days of calm period. The phase is assumed to continue from the initial precursor to ending of the immediate precursor, about 90% (5.9 weeks in 6.4 weeks) of whole nucleation period. Subsequent phases of nucleation stage, the unstable accelerating rupture phase and unstable high-speed rupture (Ohnaka and Shen, 1999, Ohnaka, 2000) are not detected by the filter of HFTs, though there are another approach using seismic data to show there are small seismic events preceding P phase by some seconds (Iio,1992; Umeda, 1990) and some a minute (Fujinawa and Noda,2020).

And the nucleation area is nearly the same with that of rupture of the mainshock, some 10 times larger compared with the previous research results of foreshock (Jones and Molnar, 1979; Ellsworth and Beronza;1995 Maeda, 1999; Scholz, 2002, Ohnaka and Matsu'ura, 2002, Yoshida and Furuya,2015). The discrepancy is assumed to be due to difference of filters to use.

3) Sensitive high-frequency tremors

The most effective HFTs of six events from the point of prediction is found to No.6 (combined high frequency tremor) which frequency is far high compared with the low frequency tremor (Obara *et al*., 2004). On the other hand, occurrence number of small micro earthquake No.1,2 are not small compared with other events, but the performance to contribute to the distinguishing is not large. However, it is meaningful to support the result that these well-known events share similar activity with the most sensitive new events No.4,5,6.

4) Effect of foreshock

In the case of the Kumamoto earthquake analyzed before the foreshock to mask effect of aftershock deduced by the foreshock. The effect of aftershock to the HFTs is very large some 3~20 times compared with before foreshock and continue two weeks to a month. On the other hand, there is only some 1 day from foreshock to mainshock when there are no large change of activity suggesting that there no serious effect of foreshock of moderate magnitude compared with main shock of major earthquake. It is suggested that activity between foreshock and mainshock is not so large but rather small, and there may be some effect due to the accelerating phase of nucleation process.

5) Real -time application

We used the observation sites based on the epicenter of sample earthquake and evaluation area using official reports, which cannot be used for real-time operation. However, we show the epicenter can be estimated using the score values first at the time of detection of each precursor to determine observation net for evaluation area.

The rule of distinguishing was deduced from analyses of three sample major earthquakes, it does not mean that future new earthquake can also distinguished. We should find robust characteristics as far as possible to use in real time when there appears any consistent term of the distinguishing table. For example the initial precursor is enough robust to be distinguished as Ps(5)>=11, Ps(0)>=8.5, and the immediate precursors is to distinguished by the threshold (Ps=7,Mv=6) at least for the cases of the three sample major earthquakes.

5. Conclusion

Investigations on earthquake prediction have been conducted in various fields, but the there are no practical method in spite of substantial progress in experimental investigation of earthquake nucleation process and field observation for slow slip using the low-frequency tremor. The critical problem is thought that there are no clear observational evidence, or seismic or tremor phenomenon in the nucleation period to practically use.

Continuous data of the Hi-net of NIED are used to find any seismic events just before occurrence of major earthquakes with the result to find two small micro-earthquakes and four new kinds of high-frequency tremor, HFTs. The catalogs of HFTs for three major earthquakes are analyzed to find if precursors are detected before major earthquakes. Thresholds for anomalous activity are defined using mean and standard deviation of those events during a month before major earthquakes. Activity of each event is quantized to be 1 or 0 (score) depending on the observed number exceeding the threshold or not. Temporal and spatial score is estimated for each event at each site. Those data are further analyzed through the distinguishing routine to find the three largest peaks corresponding to three kinds of precursors: initial, intermediate, and immediate precursor referring previous results concerning foreshocks. The results indicate that the immediate precursor can be discriminated before 0.5±0.3 weeks before, the intermediate prediction before 4.6±0.4 weeks, and initial precursor 6.4±1.2 weeks before the major earthquake.

Magnitude and epicenter of the coming earthquake is estimated from the spreading area of detected sites at the moments of distinguishing of precursors. We can estimate the three contents of prediction of earthquake (occurrence time, epicenter, magnitude) at each moment of distinguishing of precursors within confidence limit of practical use for disaster preventions actions. Those anomalous activity are assumed to be subphase of the stable quasi-static phase in the nucleation processes. In addition, the problem to use real time are proposed for future social implementation development.

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8 Figure Caption

Fig.1 Waveforms of HTMs, No.3~No.6.

Fig.2 Seismic observation sites of evaluation area and the reference area for the case of the Kumamoto Earthquake .Each area have 20 sites.

Fig.3 Typical time change of the total score of three essential frequency tremors No.4~No.6 for two months before the Kumamoto earthquake. The total sore for any HFTs means total number of seismic observation sites where any events are in the state of anomalous activity. The event No.6 has the largest and isolated peak with the sharpest increase of score just before the Kumamoto major earthquake at 21:00 JST on 14, April 2016.

9. Table Caption

Table 1 :Number of each kind of the high frequency tremor events during the sampled time-period of March 15~April 16 before the Kumamoto earthquake. Data written by bold style indicate they are two largest events at each observation site. There are large differences of occurrence number between sites amounting some 30 times, and between kind of events some 100 times.

Table 2-1：Kumamoto Earthquake

Results of examination of the second largest peak of whole events in the focal area at the first period Pe.1. It is shown that there is no event except No.4 exceeding the criteria of the imminent alarming. Moreover, the most important event No.6 does not exceed the criteria with the result that the peak is not recognized as a precursor of immediately before the major earthquake at the period 12. However, the case exceeds another criteria of short term precursor defined as 1)more than 53% events have larger score than 5 and events No.4 or No.5 exceeds maximum score of 7, and the maximum increasing speed exceeds 8 score/day.

Table2-2: Niigata Chuetsu earthquake

Result of distinguishing of largest three peaks in the case of the Niigata Chuetsu earthquake is shown. Criteria are the same as the case of Kumamoto earthquake. The three kind of precursors are distinguished as the case of the Kumamoto earthquake. There are minor differences, the occurrence period for initial precursor is No.4 period in the case of Kumamoto earthquake, and No.2 period in the case of the Niigata earthquake, for the intermediate precursor are No.7 for the Kumamoto and No.5 and 6 for the Niigata, and for the immediate precursor, both No.12 period.

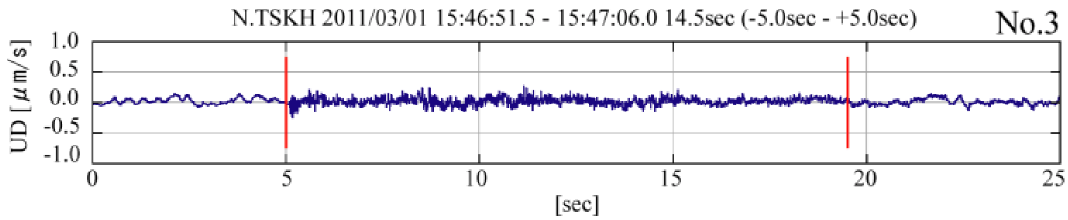
Table 3 Occurrence of three largest score peaks , initial, intemediate, and immediate precursors and simple statstical analysis indicating that each estimation can be issued 6.4±1.2 weeks, 4.5±0.4weeks, and 0.5 ±0.3 weeks, before occurrence of major earthquakes.

Table 4 Magnitude prediction M* compared with true values of three sample major earthquakes. The estimation uses the initial precursor by the event No.5 some 6 weeks before occurrence of the main shock with the confidence limit of. ±0.3.

Table 5 Epicenter prediction results compared with true values of JMA for three sample major earthquakes. The estimation use the total score of the event No.5 some 6 weeks before occurrence of the main shock with the result of confidence limit of±0.4 °.

10. Figure

Fig.1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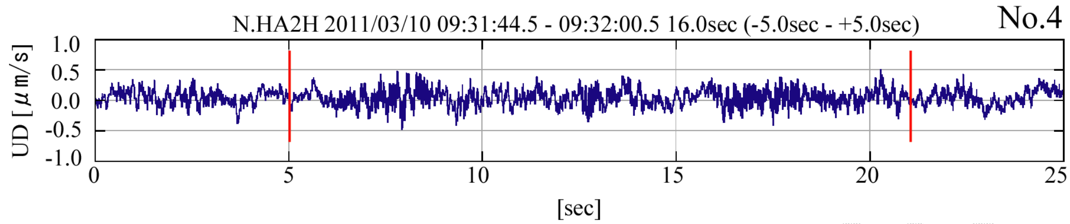
0.5
0.0
-0.5
-1.0
0
5
10
15
20
25
[sec]


N.HA2H 2011/03/10 09:31:44.5 - 09:32:00.5 16.0sec (-5.0sec - +5.0sec)
No.4
UD [μm/s]
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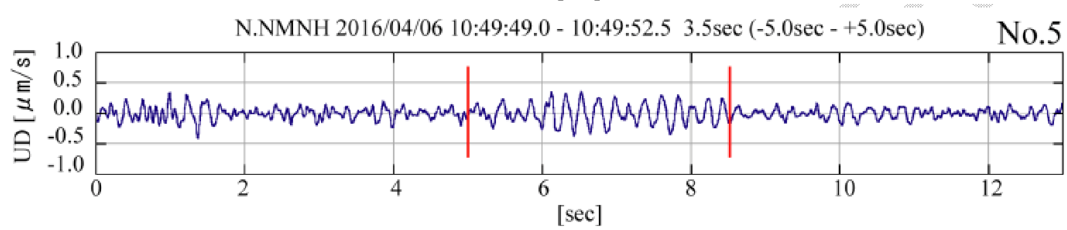
0.5
0.0
-0.5
-1.0
0
5
10
15
20
25
[sec]


N.NMNH 2016/04/06 10:49:49.0 - 10:49:52.5 3.5sec (-5.0sec - +5.0sec)
No.5
UD [μm/s]
1.0
0.5
0.0
-0.5
-1.0
0
2
4
6
8
10
12
[sec]

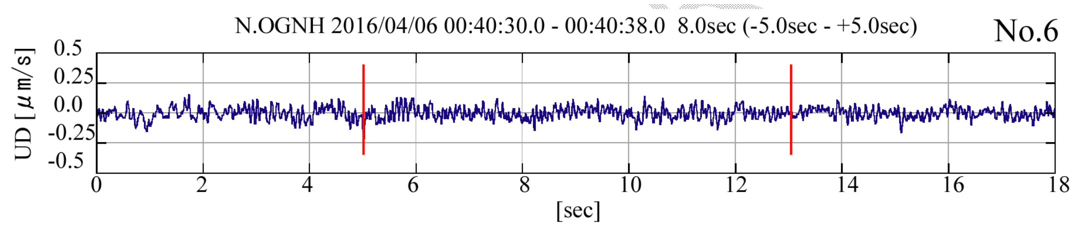
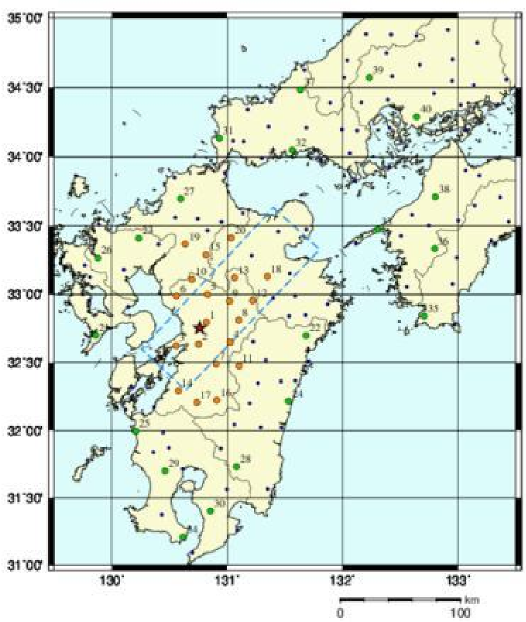

N.OGNH 2016/04/06 00:40:30.0 - 00:40:38.0 8.0sec (-5.0sec - +5.0sec)
No.6
UD [μm/s]
0.5
0.25
0.0
-0.25
-0.5
0
2
4
6
8
10
12
14
16
18
[sec]

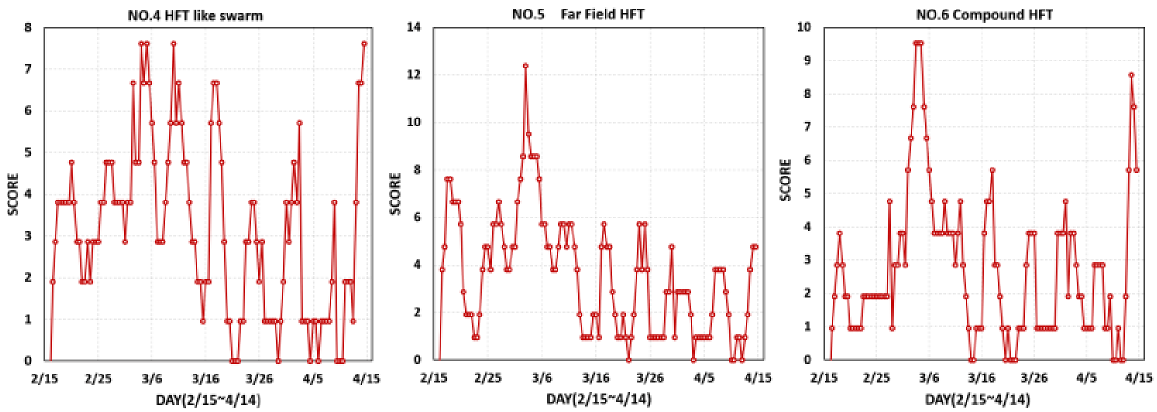
Fig. 2



Red☆ : The epicenter of the main shock
Orange○ : Vicinity of observation points (20 points)
Green○: Distant observation points (20 points)
Blue○ : Non-selected observation points
Blue frame : Destruction area(JMA)
Number : Observation point No.

	code	Station name	Prefecture	Excavation [m]	Epicentral distance[km]
Vicinity of observation points (20 points)	N.MSIH	MASHIKI	Kumamot	255	7.3
	N.TYNH	TOYONO	Kumamot	113	13.2
	N.MSMH	MISUMI	Kumamot	303	23.9
	N.YABH	YABE	Kumamot	106	27.2
	N.KKCH	KIKUCHI	Kumamot	203	27.9
	N.TMNH	TAMANA	Kumamot	103	32.0
	N.IZMH	IZUMI	Kumamot	103	32.1
	N.HKSH	HAKUSUI	Kumamot	114	32.4
	N.ASVH	ASO	Kumamot	130	32.7
	N.KHKH	KAHOKU	Kumamot	103	39.9
	N.SBAH	SHIIBA	Miyazaki	203	44.5
	N.NMNH	NAMINO	Kumamot	103	48.5
	N.OGNH	OGUNI	Kumamot	126	49.7
	N.ASKH	ASHIKITA	Kumamot	303	54.0
	N.UKHH	UKIHA	Fukuoka	203	59.6
	N.UWEH	UE	Kumamot	180	60.7
	N.HYOH	HITOYOSHI	Kumamot	126	60.8
	N.SNIH	SHONAI	Oita	232	68.9
	N.TARH	TACHIARAI	Fukuoka	440	69.1
	N.YGNH	YAMAKUNI	Oita	203	77.3
Distant observation points (20 points)	N.NGSH	NAGASAKI	Nagasaki	203	84.5
	N.KIGH	KITAGAWA	Miyazaki	213	86.6
	N.FJIH	FUJI	Saga	106	88.0
	N.KWMH	KAWAMINAMI	Miyazaki	216	93.9
	N.AKNH	AKUNE	Kagoshima	205	99.0
	N.IMRH	IMARI	Saga	105	100.1
	N.WKMH	WAKAMIYA	Fukuoka	102	105.7
	N.MJSH	MIYAKONOJO-S	Miyazaki	120	117.3
	N.KORH	KORIYAMA	Kagoshima	206	120.4
	N.KYAH	KANOYA	Kagoshima	104	150.3
	N.TYUH	TOYOURA	Yamaguchi	203	154.0
	N.HOFH	HOFU	Yamaguchi	203	161.9
	N.IKTH	IKATA	Ehime	153	164.8
	N.YKWH	YAMAGAWA	Kagoshima	206	172.0
	N.OOTH	OTSUKI	Kochi	102	182.4
	N.HIYH	HIYOSHI	Ehime	203	200.8
	N.MTMH	MUTSUMI	Yamaguchi	203	208.2
	N.TBEH	TOBE	Ehime	137	217.9
	N.TGUH	TOGOUCHI	Hiroshima	105	243.5
	N.KURH	KURE	Hiroshima	104	243.8

Fig. 3


NO.4 HFT like swarm
SCORE
DAY(2/15~4/14)
NO.5 Far Field HFT
SCORE
DAY(2/15~4/14)
NO.6 Compound HFT
SCORE
DAY(2/15~4/14)

11. **Table**

Table 1.

Observation Site		**Total**	**kind of events**					
No.	**Name**	**Number of events**	**1.near field SME**	**2.remote field SME**	**3.near field HFT like string**	**4. near field HFT like swarm**	**5.far field HFT**	**6.compo-und HFT**
1	Mashiki	31,347	1,105	**1,808**	103	194	**26,727**	1,410
2	Toyono	17,696	1,047	879	1,733	**2,208**	**10,576**	1,253
3	Misumi	2,841	**1,164**	279	137	212	**874**	175
4	Yabe	1,053	**310**	57	91	**291**	251	53
5	Kikuchi	7,236	**1,970**	180	**2,249**	1,684	886	267
6	Tamana	8,777	1,781	240	**2,648**	1,443	**1,949**	716
7	Izumi	1,410	**322**	16	212	269	**504**	87
8	Hakusui	10,399	620	522	**1,664**	1,011	**5,921**	661
9	Aso	26,372	228	345	509	**4,212**	**19,508**	1,570
10	Yamagashi	26,188	**6,175**	768	**8,442**	5,542	3,550	1,711
11	Shiiba	462	73	19	66	**102**	**168**	34
12	Namino	26,307	792	865	927	**5,396**	**15,858**	2,469
13	Oguni	18,858	906	191	1,197	**13,091**	**2,230**	1,243
14	Ashikita	3,779	**2,021**	45	298	470	**852**	93
15	Ukiha	968	**292**	52	**283**	132	126	83
16	Kami	12,392	**4,769**	511	1,750	1,081	**3,913**	368
17	Hitoyoshi	21,831	1,326	246	3,199	**11,386**	**3,858**	1,816
18	Shounai	6,631	**621**	460	249	153	**4,919**	229
19	Tachiarai	1,356	**217**	118	87	46	**828**	60
20	Yamakuni	1,679	**580**	115	69	89	**616**	210
		sum for 20 sites	26,319	7,716	25,913	**49,012**	**104,114**	14,508
		cases of top 2	11			6	16	

Table 2－１,Table 2-2

Table 2-1

Kumamoto EQ		(a) Focal Area												(b) Reference Area											
		Initial Prec.			intermediate Prec.			calm Pe.(sample)			immediate Prec.			Initial Prec.			intermediate Prec.			calm Pe.(sample)			immediate Prec.		
disting. result		O			O			X			O			X			X			X			X		
event		Feb.29			March .15			March. 30			April(10)			Feb.29			March .15			March. 30			April(10)		
		Pe4		94%	Pe7		88%	Pe10		6%	Pe12		94%	Pe4		88%	Pe7		6%	Pe10		76%	Pe12		82%
No.	name	day	max score	max. veloci.	day	max score	max. veloci.	day	max score	max. veloci.	day	max score	max. veloci.	day	max score	max. veloci.	day	max score	max. veloci.	day	max score	max. veloci.	day	max score	max. veloci.
1	N. field small Mi.Ea.	19.5	4.8	3.8							60.5	4.8	3.8	19.5	4.8	1.9	32.0	4.8	3.8				60.5	4.8	5.7
2	F.field small Mi.Ea.	18.5	7.6	3.8	33.0	4.8	3.8	46.5	4.8	5.7	59.0	5.7	5.7	19.0	5.7	3.8	33.0	5.7	7.6				60.5	4.8	3.8
3	N.field HFT(swarm t.)	19.0	6.7	5.7	32.5	7.6	5.7				59.5	5.7	3.8	19.0	4.8	3.8	31.5	4.8	3.8	45.5	6.7	5.7			
4	N. field HFT(string t.)	19.0	7.6	5.7	32.5	6.7	7.6	48.5	5.7	3.8	60.5	7.6	5.7	17.5	4.8	3.8	33.0	4.8	3.8	45.5	7.6	5.7	60.5	5.7	5.7
5	F.field HFT	18.0	12.4	7.6	32.5	5.7	7.6	45.0	4.8	3.8	60.0	4.8	3.8	18.0	7.6	5.7	31.5	6.7	7.6						
6	Compund t. HFT	18.5	9.5	5.7	33.0	5.7	5.7	47.0	4.8	5.7	59.5	8.6	7.6	18.5	6.7	3.8							60.5	6.7	3.8

Table 2-2

Niigata EQ.		(a) Focal Area												(b) Reference Area											
		Initial Prec.			intermediate Prec.			calm Pe.(sample)			immediate Prec.			Initial Prec.			intermediate Prec.			calm Pe.(sample)			immediate Prec.		
disting. result		O			O			X			O			X			X			X			X		
event		May. 22			Jun. 21			July. 1			July. 11			Jun. 21			21-Jun			1-Jul			July. 11		
		Pe2		100%	Pe2		100%	Pe4		12%	Pe6		88%	Pe2		100%	Pe6		100%	Pe10		12%	Pe12		29%
No.	name	day	max score	max. veloci.	day	max score	max. veloci.	day	max score	max. veloci.	day	max score	max. veloci.	day	max score	max. veloci.	day	max score	max. veloci.	day	max score	max. veloci.	day	max score	max. veloci.
1	N. field small Mi.Ea.	9.0	4.8	5.7	28.5	5.7	3.8							8.0	4.0	2.0	28.5	5.0	4.0						
2	F.field small Mi.Ea.	7.0	8.6	5.7	27.0	6.7	1.9				55.5	4.8	5.7	6.5	7.0	2.0	29.0	7.0	4.0						
3	N.field HFT(swarm t.)	6.0	4.8	3.8	25.0	5.7	3.8				56.0	4.8	3.8	8.0	6.0	4.0	28.0	7.0	4.0						
4	N. field HFT(string t.)	8.5	4.8	1.9	27.5	4.8	5.7	45.5	4.8	3.8	56.0	6.7	5.7	7.5	9.0	6.0	28.0	8.0	6.0	49.0	4.8	5.7			
5	F.field HFT	8.0	11.4	6.0	29.5	6.7	5.7				56.5	5.7	3.8	7.5	6.0	4.0	27.5	6.0	6.0						
6	Compund t. HFT	7.0	8.6	3.8	27.5	4.8	3.8				56.0	9.5	13.3	7.5	8.0	4.0	28.0	7.0	4.0						

Table 3.

Precursor \ Earthquake	Kumamoto (Wk)	Niigata (Wk)	Iwate (Wk)	Mean (Wk)	Devation (Wk)
Initial	6.3	7.6	5.3	6.4	1.2
Intermediate	4.1	4.8	4.5	4.5	0.4
Immediate	0.3	0.8	0.3	0.5	0.3

Table 4

Earthquake \ Parameter	Ps(5)	M*	Mj	ΔMj
Kumamoto	12.5	7.1	7.3	-0.2
Niigata	11.5	7.1	6.8	0.3
Iwate-nairiku	13.5	7.1	7.2	-0.1

Table 5

Initial Precursor.

Parameter / Earthquake	Mj	No.5	Epicent. (JMA)		Epicent.(estimate)		Confidence Lim.	
		Ps(5)	E(°)	N(°)	E(°)	N(°)	E(°)	N(°)
Kumamoto	7.3	13	32.5	130.5	32.7	130.8	0.2	0.4
Niigata	6.8	11	37.6	138.7	37.2	138.8	-0.4	0.1
Iwate	7.2	14	39	140.9	39.1	140.8	0.03	-0.1