DOI: http://dx.doi.org/10.12989/was.2004.7.5.345

Typhoon damage analysis of transmission towers in mountainous regions of Kyushu, Japan

Eriko Tomokiyo†, Junji Maeda‡ and Nobuyuki Ishida‡†

Depertment of Archtecture, Kyushu University, Japan

Yoshito Imamura‡‡

Kyushu Electric Power Co., Inc., Japan

(Received November 24, 2003, Accepted June 24, 2004)

Abstract. In the 1990s, four strong typhoons hit the Kyushu area of Japan and inflicted severe damage on power transmission facilities, houses, and so on. Maximum gust speeds exceeding 60 m/s were recorded in central Kyushu. Although the wind speeds were very high, the gust factors were over 2.0. No meteorological stations are located in mountainous areas, creating a deficiency of meteorological station data in the area where the towers were damaged. Since 1995 the authors have operated a network for wind measurement, NeWMeK, that measures wind speed and direction, covering these mountainous areas, segmenting the Kyushu area into high density arrays. Maximum gusts exceeding 70 m/s were measured at several NeWMeK sites when Typhoon Bart (1999) approached. The gust factors varied widely in southerly winds. The mean wind speeds increased due to effects of the local terrain, thus further increasing gust speeds.

Keywords: NeWMeK; winds measurement; transmission tower; typhoon damage; gust factor; terrain effect.

1. Introduction

In the 1990s, a number of strong typhoons hit the Kyushu area of Japan, inflicting severe damage on many power transmission facilities, public buildings, houses, and so on. Since 1995 the authors have operated a network for wind measurement in Kyushu, which is called NeWMeK (Maeda, *et al*. 1994, 1995 and 1996). This network consists of high-density arrays covering the Kyushu area. The authors continue to collect strong wind data regarding potential emergency situations attributable to typhoons. This paper reports on the features of recent typhoons and the damage they have inflicted on transmission towers. In particular, the authors discuss the wind characteristics of Typhoon Bart (1999) and the damage to towers located in the mountainous regions along with the distribution and direction of fallen trees.

† Research Associate
‡ Professor
‡† Ph.D. Student
‡‡ Manager

2. Features of recent typhoons and their damage to transmission towers

In the 1990s, four strong typhoons hit the Kyushu area of Japan: Kinna (1991), Mireille (1991), Yancy (1993), and Bart (1999). The storms they created severely damaged many transmission facilities. Photo 1 shows an example of a damaged tower.

Fig. 1 illustrates the path of each typhoon and the location of the damaged transmission towers in the Kyushu area. Fig. 2 shows the number of towers damaged by each typhoon. Kinna and Mireille passed through northern Kyushu, inflicting extensive damage to twenty-four towers. Yancy passed through the southern area and damaged nineteen towers. Bart hit the central areas, leaving fifteen towers broken. We can see that all of the damaged towers were located on the eastern side of each typhoon’s path.

Fig. 3 shows the maximum wind speeds and maximum gust speeds of each typhoon, as measured at government meteorological stations (Maeda, *et al*. 2000). Fig. 4 shows the gust factors of each typhoon and by each direction as measured at the meteorological stations. Gust factors were defined

Photo 1 Damaged towers by Typhoon Bart

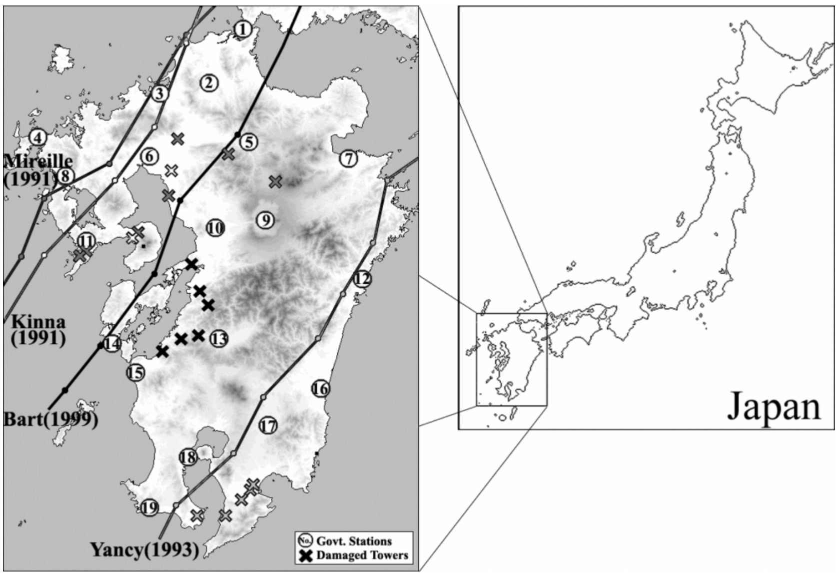

Fig. 1 Location of meteorological stations and paths of recent typhoons

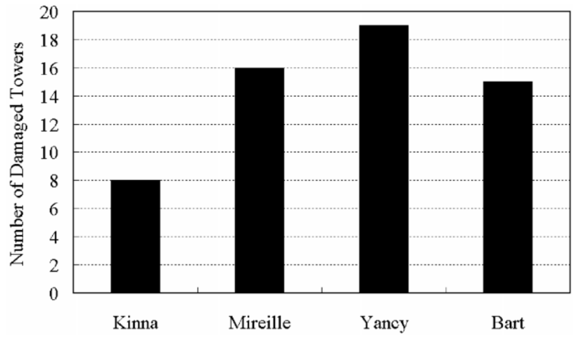

Fig. 2 Number of damaged towers

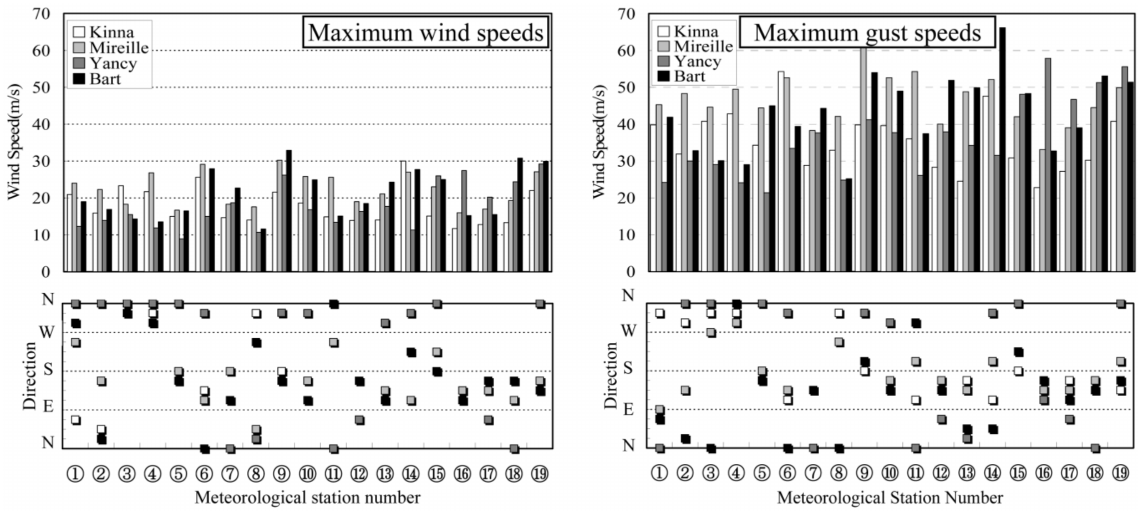

Fig. 3 Maximum wind speeds and maximum gust speeds of individual typhoons

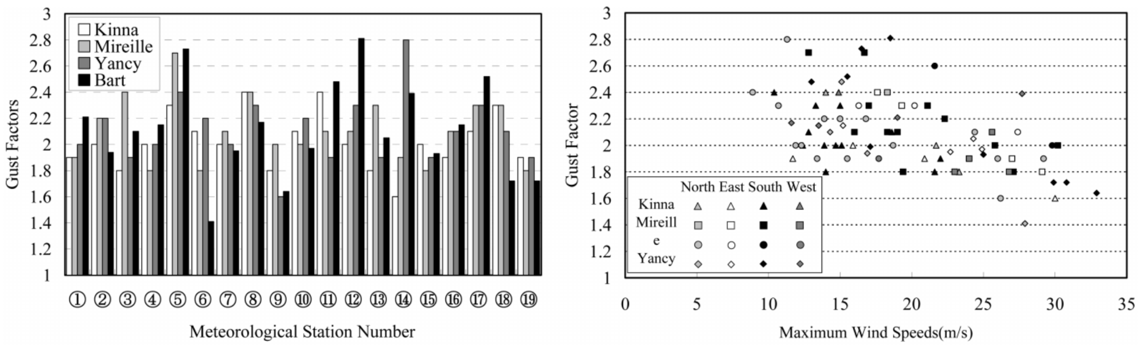

Fig. 4 Gust factors of individual typhoons

as the ratio of maximum gust speed to maximum wind speed. Mireille, with a maximum gust speed of 60.9 m/s at station No. 9, had the storm zone with the largest radius, 200 km, causing the largest range of wind damage among the four typhoons. In contrast, the moderate storm zones of Kinna, Yancy, and Bart resulted in local damage in the Kyushu area. However, Yancy and Bart caused serious damage to many pieces of power transmission equipment. Yancy's maximum gust speed was 57.9 m/s at No.16. Bart's maximum gust speed was 66.2 m/s at No.14, and four 500 kV high-voltage transmission towers in mountainous areas fell when Bart passed. As shown in Fig. 4, gust factor values were over 2.0 at several government stations. It is generally the case that the higher the wind speed, the lower the gust factor. However, the gust factor value reached 1.8 even when wind speeds were over 30 m/s, as illustrated in Fig. 4. Although the mean wind speeds were higher for southerly winds, the wind gusts also increased. In northerly winds, the gust factors were low.

Unfortunately, it is unknown whether the damaged towers were subject to same wind conditions as were recorded in the downtown areas where the meteorological stations are located. Further, the relationship between the high-gust factor and damage distribution remains unclear.

3. Detailed structure of wind distribution due to Typhoon Bart

3.1. Characteristics of Typhoon Bart based on NeWMeK data

The authors formed and began to operate NeWMeK in 1995. The network's observation sites cover the mountainous area, where damaged towers are most often found. We report the characteristics of Typhoon Bart based on NeWMeK data.

3.1.1. Outline of NeWMeK

NeWMeK is a wide-area network system intended to measure wind speed and direction, segmenting the Kyushu area into high-density arrays. The features of this progressive system, which enables the collection of more detailed and localized wind data, include the following:

(1) The system has 122 observation points at approximately 20 km intervals throughout the Kyushu area.

(2) An anemometer is positioned at the top of each transmission tower designed as an observation point. (Photo 2) The towers range in height from 12 m to 195 m, and have elevations between 0 m and 1,118 m from sea level. Figs. 5 and 6 show the anemometerís positioned height from the ground and the elevation of the observation points, respectively.

Photo 2 Anemometer

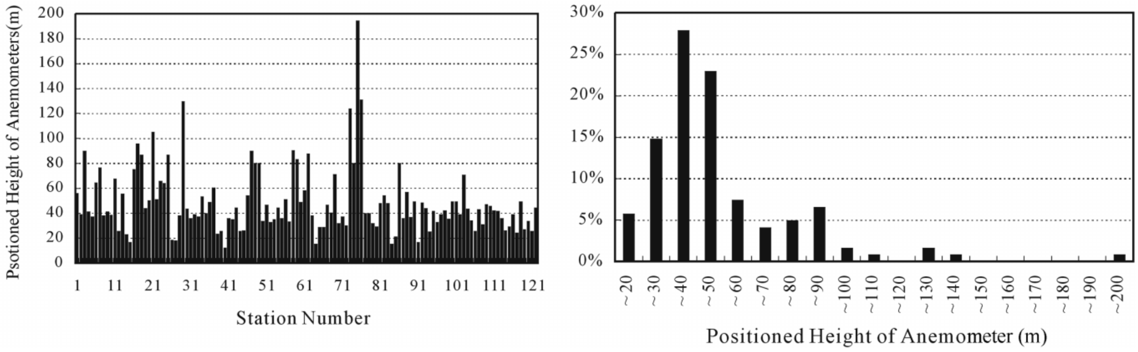

Fig. 5 Positioned height of anemometer from ground level

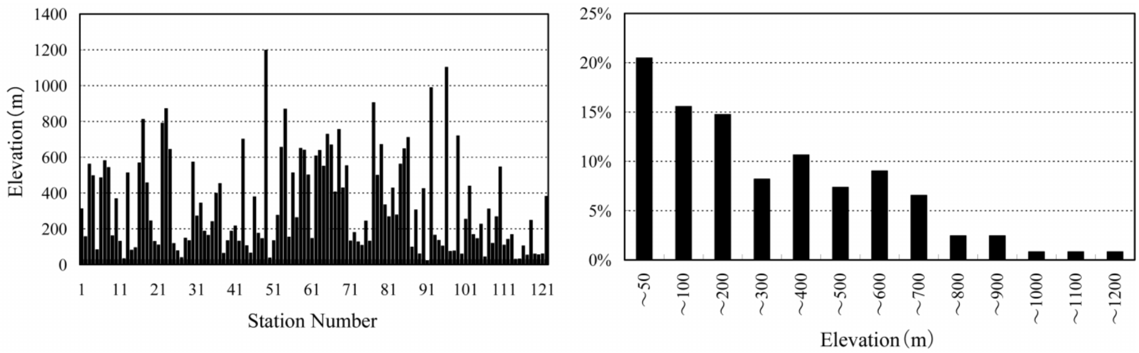

Fig. 6 Elevation of observation points

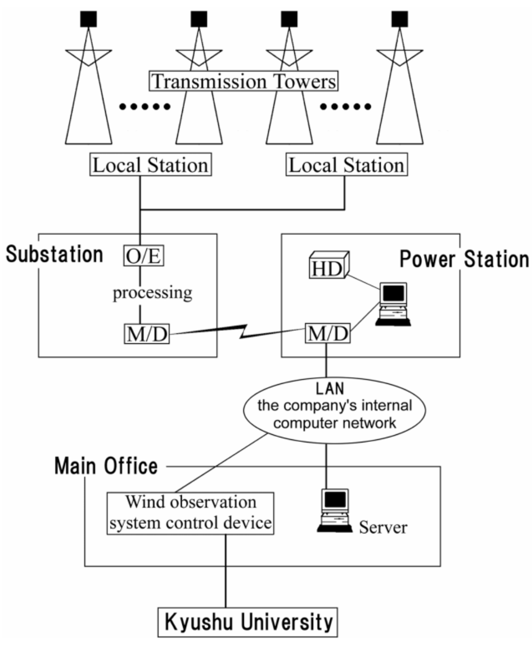

Fig. 7 Procedure for acquisition of NeWMeK

(3) Windmill anemometers with a measurement range of 0 m/s to 90 m/s and a distance constant of 8 m are used. Both wind speed and direction are scanned at a 4 Hz sampling rate, and the wind direction is indicated by 16 positions.

(4) Measurement data is sent to the Kyushu Electric Company's 18 power system maintenance offices via optical cables, as illustrated in Fig. 7. The Head Office and the maintenance offices collect the data regarding wind speed and direction continuously in real time.

(5) Wind data is scanned every 0.25 seconds, and the mean value of four samples is sought as one second duration data. The wind speed value (m/s) is rounded off to the first decimal point. The authors have collected the one-second duration data comprising mean speed and direction.

Since 2002, the same observation points have been equipped with atmospheric pressure gauges. They measure pressure data when a tornado as well as typhoon passes. The atmospheric pressure data are additionally useful for estimating local wind conditions.

3.1.2. Characteristics of Typhoon Bart based on NeWMeK data

Fig. 8 indicates the locations of the damaged towers, Bart's route, and the nearby NeWMeK sites. As shown in the figure, Bart's maximum gust distribution throughout Kyushu can be obtained using the accurate data measured at the NeWMeK observation points on September 24, 1999. Fig. 9 shows the maximum gust distribution using data at 3, 4 and 5 a.m. In the figure, the symbol "■" indicates the NeWMeK's observation points. This was approximately the time when several transmission towers in the area collapsed. Fig. 10 shows the time evolution of wind speed and direction at several NeWMeK sites. Several sites suffered partial losses of wind data due to power outage. High wind speeds, exceeding a maximum gust of 70 m/s, were measured at several of the NeWMeK sites. In Fig. 8 we can see that particularly high wind gusts, exceeding 60 m/s, were observed at about 5 a.m. in central Kyushu. These were southeasterly and southerly winds.

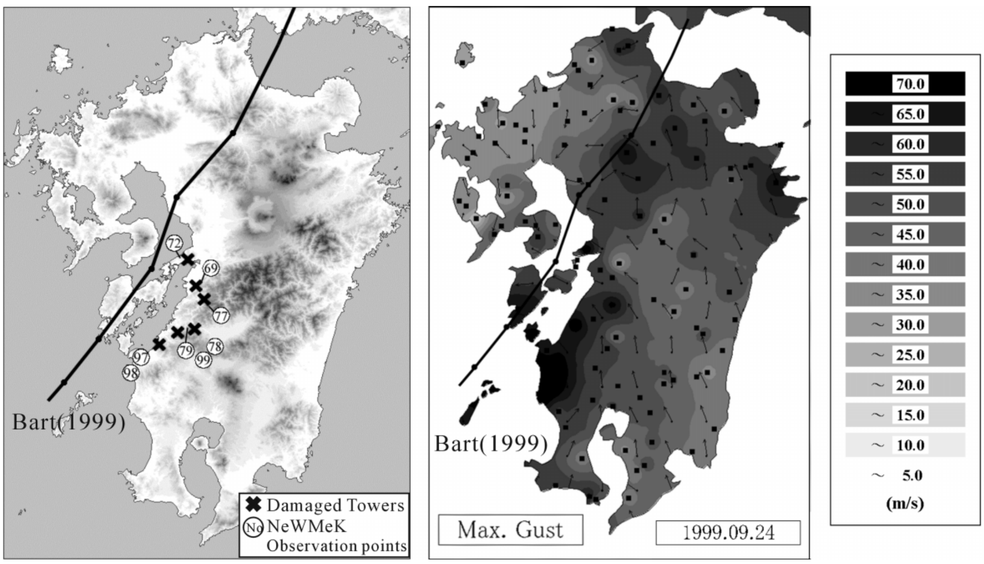

Fig. 8 NeWMeK observation points and maximum gust distribution throughout Kyushu

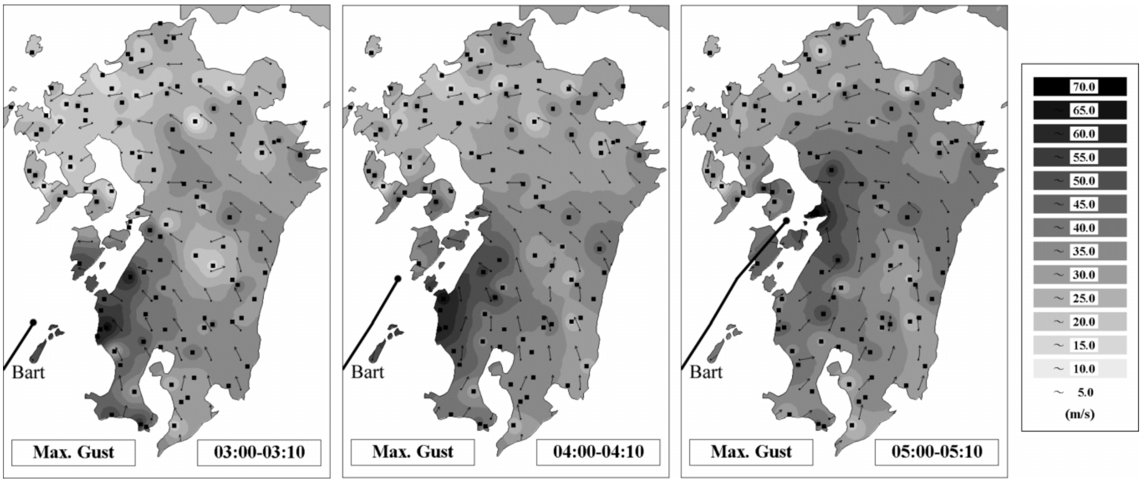

Fig. 9 Time evolution of maximum gust distribution throughout Kyushu at 3, 4 and 5 a.m.

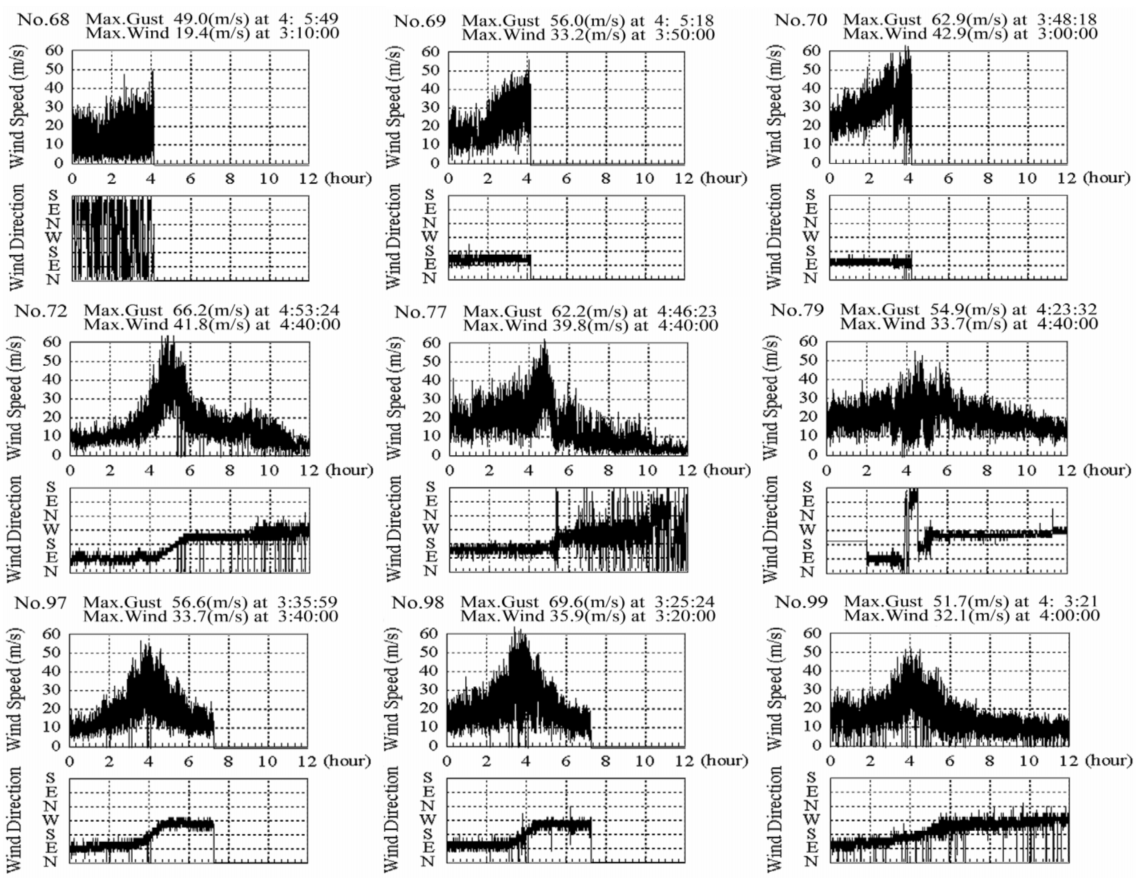

Fig. 10 Wind speeds and directions recorded at NeWMeK observation points

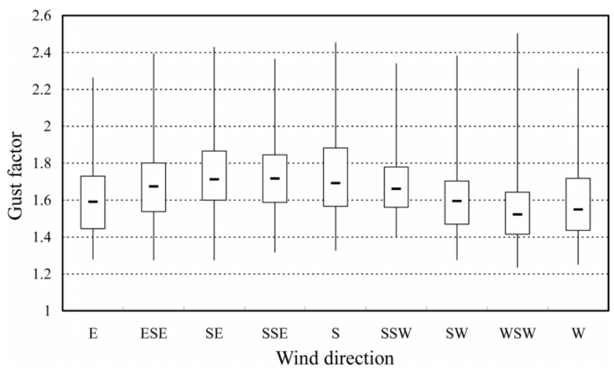

Fig. 11 Gust factors of southerly winds (mean speeds exceeding 20 m/s)

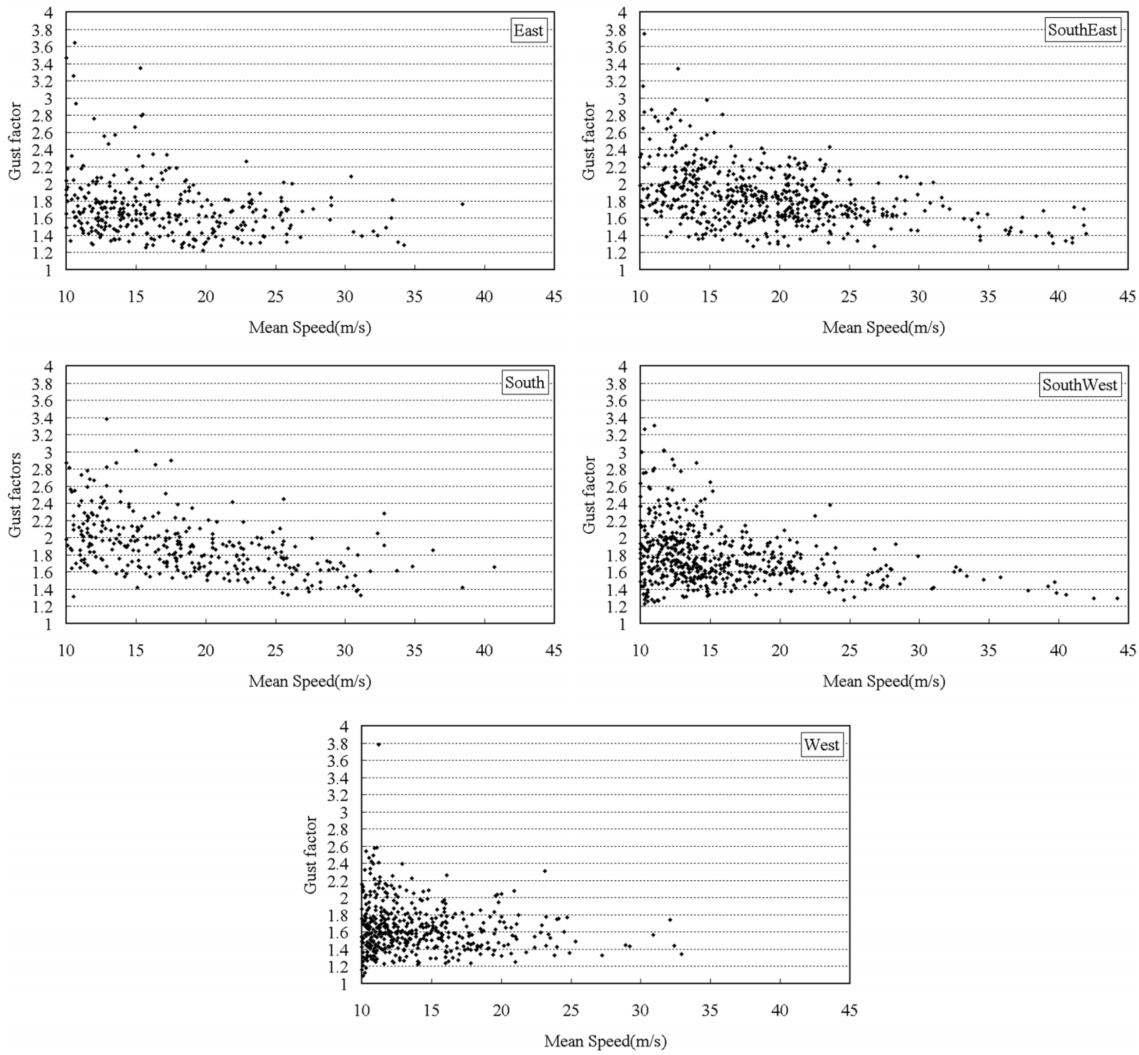

Fig. 12 Gust factors by each wind direction

Fig. 11 shows the gust factors of southerly winds through a box-plot, using the records of mean speed exceeding 20 m/s. The box-plot indicates the data distribution. The line inside the rectangle indicates the median of the distribution. The upper and lower boundaries of the rectangle indicate the upper quartile and the lower quartile, respectively. Two lines are drawn from the rectangle to the extreme values. As shown in Fig. 10, the wind directions turned from east to west as the typhoon passed. The gust factors of southerly winds varied widely. The values were high, at around 1.7. The gust factors were around 1.5 in the westerly winds. Fig. 12 shows gust factors by each wind direction. It shows that wind speeds were high in southerly, southeasterly, and southwesterly winds. As shown in Fig. 12, the higher the wind speed, the lower the gust factor. However, at the time of the typhoon the value of the gust factor could be over 2.0 even when wind speeds were over 30 m/s. Although the mean wind speeds were high, the wind gusts increased when Bart approached. This is the reason the towers were seriously damaged.

3.2. Characteristics of Typhoon Bart based on the fallen timber

Thirteen towers including four 500 kV transmission towers collapsed due to Typhoon Bart. A high-voltage transmission tower had never before collapsed in Kyushu. The breakdown of the towers damaged by Bart is listed in Table 1. As well, a great number of trees from the timber near the damaged towers fell due to the winds. Damage to timber is influenced by the kinds of wood or the properties of the soil. Where there weren’t meteorological stations or a nearby NeWMeK site, the authors were able to assume the characteristics of local winds based on the distribution of the fallen trees. Thus, the authors take interest in these damaged towers and fallen timber.

The authors surveyed the distribution of the fallen timber in two areas. Fig. 13 illustrates the location of damaged towers and the area of fallen timber in the shallow valley terrain. In the figure, the arrows represent the direction of the collapsed towers and fallen timber. The black square locates the observation point of NeWMeK No.72. In this area four 500 kV transmission towers collapsed. Wind directions were southeast to south at about 5 a.m., when the maximum gust speed reached around 65 m/s based on NeWMeK data. The observed record at No.72 is shown in Fig. 10. The fallen timber was distributed on southward-facing slopes and the trees fell along the wind direction. Photo 3 shows the damage to timber.

In this area, we think that the winds became stronger as they rushed up the incline of the southward-facing slopes. In addition, the mountainous ridge near the tower of No.162 has a shallow valley running from north to south, so the winds that became strong on the slopes became even stronger in the shallow valley.

Fig. 14 shows the location of damaged towers and the area of fallen timber in the deep valley-river terrain. In the figure, the black square marks locate the NeWMeK points of No.68 and 69. In

Table 1 Transmission towers collapsed by Typhoon Bart

Tower number		Collapsed	Broken	Total
161-164	(500 kV)	4		4
9	(66 kV)	1		1
111-113	(110 kV)	2	1	3
89-103	(110 kV)	6	1	7
Total		13	2	15

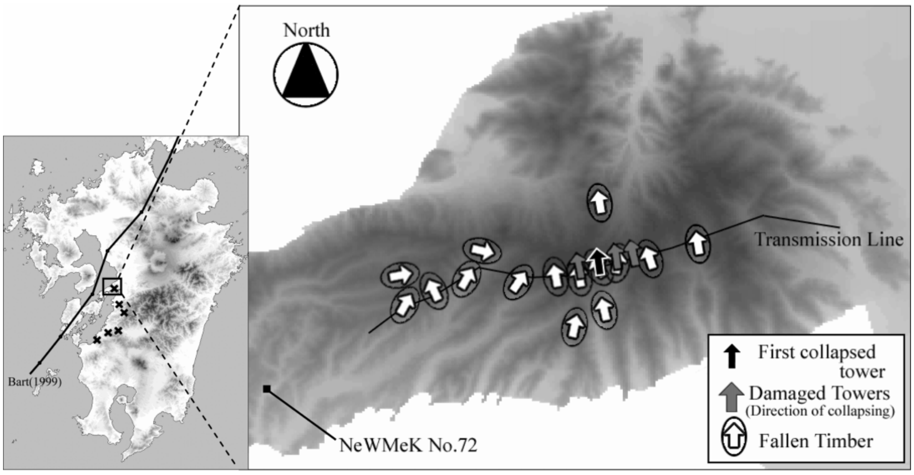

Fig. 13 The damaged towers and fallen timber (The shallow valley terrain)

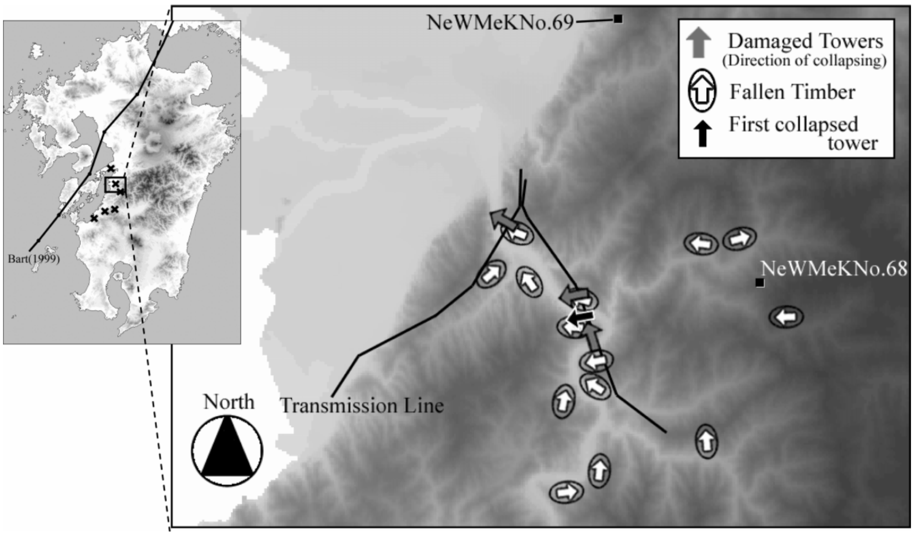

Fig. 14 The damaged towers and fallen timber (The deep valley terrain)

Photo 3 The distribution of the fallen timbers (the shallow valley terrain)

Photo 4 The distribution of the fallen timbers (the deep valley terrain)

this area two towers collapsed and one was broken. Photo 4 shows the damage to the timber. Maximum wind gust speeds exceeded 50 m/s on the NeWMeK record. The wind directions were southeast to south at about 5 a.m. The observed records of No.68 and No.69 are shown in Fig. 10. The areas of damaged trees are spread discontinuously; most were found in areas of the river's curve. The falling directions of the timbers didn't always correspond to the representative wind directions of Bart. Rather, many of the directions coincided with the valley direction. This direction was identical with that of the tower that collapsed first, too. It is guessed that wind converging along the deep valley changed its wind direction and increased its speed much more.

Table 2 The critical wind speed of the damaged towers and the estimated maximum gust speeds at a height of 10 m

		Critical wind speed(m/s)		Estimated maximum gust speed
Tower number		Main post	Bracing member	
161	(500 kV)	65.6	60.6	67.2
162		68.0	60.2	75.7
163		85.6	72.9	58.6
164		68.5	64.9	41.7
9	(66 kV)	60.8	53.0	61
111	(110 kV)	69.2	55.9	61
112		58.3	51.9	61
113		61.4	57.7	61
89	(110 kV)	57.9	76.8	61
90		62.2	58.6	61
99		62.0	67.8	61
100		63.6	87.6	61
101		56.8	65.3	61
102		119.6	102.1	61
103		59.9	80.3	61

No. : collapsed first

3.3. Damage of the transmission towers by Typhoon Bart

The comparisons between the maximum gust speeds at the collapsed towers and their critical design wind speeds are significant. The maximum gust speeds were estimated based on the data observed at the NeWMeK points and the meteorological stations. These estimated wind speeds were almost consistent with the estimates by the wind flow simulation technique developed by Central Research Institute of Electric Power Industry (Nakamura, *et al*. 2000). On the other hand, the critical wind speeds of the towers were estimated by Design Standards on Structures for Transmissions (JEC-127-1979, 1979). A breakdown of the critical wind speeds and estimated maximum gust speeds is presented in Table 2.

The maximum gust speeds exceeded the critical wind speed of the towers on towers No.162, 9, 112, 89 and 101; these were confirmed to be the towers that collapsed first. The adjoining towers were guessed to have been involved in changes in tensile forces of the transmission lines from the first collapsed towers.

4. Conclusions

Recently, four severe typhoons have hit the Kyushu area of Japan and inflicted damage on power transmission facilities. The gust factors, based on data gathered by meteorological stations, were high when the typhoons passed. But, without more detailed data, it was difficult to clarify the local wind conditions that caused the damage to the towers located in mountainous areas.

NeWMeK is a wide-area network system intended to measure wind speed and direction in Kyushu. High wind speeds were measured at several of the NeWMeK sites when Typhoon Bart passed. High wind gusts, exceeding 70 m/s, were observed at about 5 a.m. on September 24, 1999. These were southerly winds. The gust factors varied widely between southeasterly and southerly winds when the typhoon was approaching. The gust factors did not decrease, even when the wind speeds were high.

The towers were damaged by winds that became stronger due to the effect of the local terrain or by being involved in changes in tensile forces of the transmission lines of the towers that had already collapsed. These towers were collapsed due to a combination of the above factors.

Acknowledgements

The authors would like to thank Kyushu Electric Power Co., Inc. and Kyushu Electric Engineering Consultants Inc. for collecting data and for maintaining NeWMeK.

References

JEC-127-1979 (1979), Design Standards on Structures for Transmissions, Standard of the Japanese Electrotechnical Committee.

Maeda, J., Tomonobu, N., Miyazaki, F. and Fukumoto, Y. (1994), "Wind observation analysis using a network of wind measurement arrays of high density in the Kyushu area", *Proceedings of the 13th National Symposium on Wind Engineering*, Tokyo, Japan, 49-54, Dec.

Maeda, J., Tomonobu, N. and Miyazaki, F. (1995), "Wide area network system of wind measurement utilizing power transmission line systems", *Proceedings of the First International Symposium on Cable Dynamics*, Liege, Belgium, 537-544.

Maeda, J. (1996), "Gusty wind observation utilizing a measurement array of high density", *Abstract of Third International Colloquium on Bluff Body Aerodynamics & Applications*, Blacksburg, Virginia, USA, C-IV-1-4.

Maeda, J., Tomokiyo, E., Noguchi, H. and Ishida, N. (2000), "Wind characteristics of typhoon bart based on some observations", *Proceedings of 16th National Symposium on Wind Engineering*, Tokyo, Japan, 95-100.

Nakamura, H., Tanaka, N., Nakazono, M., Matsuyama, A. and Tomonobu, N. (2000), "Studies on the local wind resistance design of transmission tower-conductor systems (2nd Report, A Simple Criterion of Special Topography and an Estimation Method of Design Wind Velocity Based on Numerical Simulation)", *J. Wind Eng.*, **82**, 49-60.

CC