Seismicity of Matsushiro micro earthquake swarm (*)

J. C. Drakopoulos (**) - H. N. Srivastava (***) - T. Terashima

Ricevuto il 10 Agosto 1970

Summary. — During the peak swarm activity at Matsushiro, micro-earthquakes were recorded at Suzaka and Matsushiro on FM magnetic data recorder. The data so obtained were utilized to study the variations of b in Gutenberg-Richter's frequency-magnitude relationship given by $\log N = A - bM$, where M is the magnitude and N is the number of earthquakes. It was found that the value of b in Matsushiro swarm is more or less constant in short intervals of time but changes significantly for two different periods of observations of Suzaka. The value of b from the observations at Matsushiro has also been found to be rather small as compared to that at Suzaka.

Riassunto. — Durante l'intenso periodo di attività microsismica avvenuto a Matsushiro, le microscosse furono registrate a Suzaka e Matsushiro con un registratore a nastro magnetico FM. I dati così ottenuti furono utilizzati per studiare le variazioni di b. dalla formula di Gutenberg-Richter che lega la frequenza alla magnitudo

$$\log N = A - bM$$

dove M è la magnitudo ed N è il numero dei terremoti presi in esame.

Dalle osservazioni fatte a Matsushiro è stato trovato che il valore di b per brevi intervalli di tempo è più o meno costante, mentre varia sensibilmente a Suzaka quando si considerano due diversi periodi sismici. Dal confronto delle osservazioni si è potuto constatare che il valore di b relativo a Matsushiro è alquanto più piccolo di quello calcolato per Suzaka.

1. - Introduction.

Seismicity of Matsushiro earthquake swarm has been the subject of interest for the last few years. Some seismologists namely Suyehiro,

---

(*) International Institute of Seismology and Earthquake Engineering Tokyo, Japan.

(**) Seismological Laboratory, Athens University, Greece.

(***) India Meteorological Department, Lodi Road, New Delhi-3, India.

et al ([1]) studied the seismicity of the region for felt earthquakes or earthquakes of rather large magnitude. In a series of papers, Hamada and Hagiwara ([2]) reported detailed results of the micro and ultra micro-earthquakes in the area of Matsushiro using high sensitivity tripartite observations recorded on magnetic data recorder. They found that the value of b in Gutenberg-Richter's relationship ([3]) did not change significantly with respect to different intervals of time. Further, the value of b during the abnormally high activity was similar to that for normal seismic activity. They also found that the Ishimoto-Iida's coefficient m ([4]) examined with respect to ultra micro-earthquakes showed larger value before two climaxes of seismic activity at the beginning of April and the end of August and the smaller value appeared just after the climaxes.

The party for seismographic observation and seismological section ([5]) obtained the value of m for every 10 days and the values of b for each month since March 1966. The value of m at each station of observation showed a similar behaviour.

The object of the present paper is to study the seismicity in particular the variations of b in Gutenberg-Richter's relationship ([3]) within shorter interval of time than studied hitherto with reference to the micro-earthquakes recorded at Suzaka and Matsushiro and compare the results with those of other investigators.

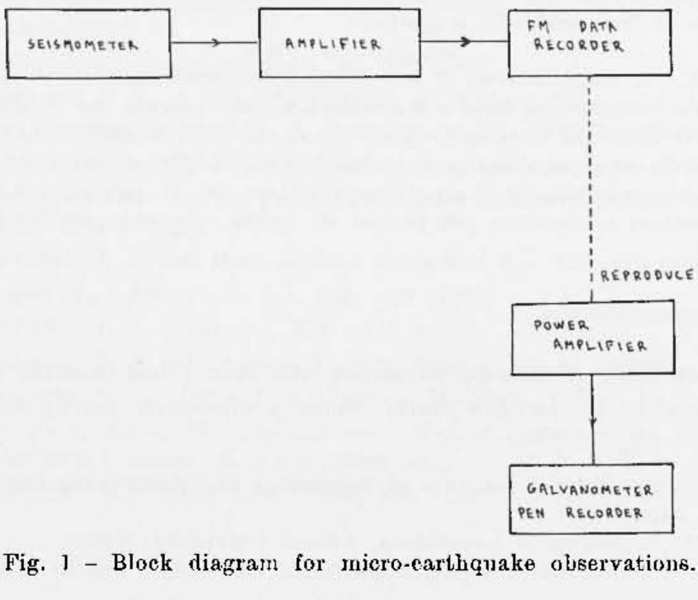

Fig. 1 - Block diagram for micro-earthquake observations.

Table I – SUZAKA I (1965)

Monitor N°	Period of Observation From		Period of Observation To		Number of Earthquakes
1	Dec. 20,	14h10m	Dec. 20,	16h35m	12
2		16 52		23 25	45
3	Dec. 21,	08 09	Dec. 21,	12 42	31
4		18 42		20 40	2
5		23 45	Dec. 22,	00 48	6
6	Dec. 22,	00 51		01 44	9
7		01 46		08 15	35
8		08 17		12 31	34
9		14 10		16 55	33
10		17 37		18 51	0
11		18 51		20 23	6
12		20 38	Dec. 23,	00 27	37
13	Dec. 23,	00 30		07 00	91
14		09 00		11 53	21
15		12 32		18 00	52
16		18 05	Dec. 24,	00 40	33
17	Dec. 24,	00 41		00 58	3
18		01 10		07 30	40
19		08 09		14 33	37
20		14 34		21 16	52
21		21 17	Dec. 25,	00 06	18
22	Dec. 25,	00 14		07 30	41
23		08 34		13 05	26
24		13 13		16 12	17
25		16 17		19 47	32
26		19 48		00 55	61
27	Dec. 26,	00 56	Dec. 26,	07 30	85
		Suzaka II (1966)			
50	Jan. 13,	01h12m	Jan. 13,	08h00m	62
51		10 23		12 23	14
52		12 25		15 59	15
53		16 05		17 10	8
54		17 15		21 36	60
55		21 58	Jan. 14,	00 10	56
56	Jan. 14,	00 11		06 45	67
57		10 05		12 14	7
58		12 15		18 52	159
59		19 39		21 50	74
60		21 51		23 35	93
		Matsushiro (1966)			
1	May 21,	00h10m	May 21,	04h44m	510

2. – Instrumentation and Collection of Data.

The experimental arrangement for the observation of micro-earthquakes is given in Fig. 1. The output signals from three moving coil transducers of 1 sec free period with $h \doteq 0.65$ were recorded by FM magnetic tape recorder after amplification.

The sensitivity of the transducer is 3.5 Volt/kine. The response of the data of FM was flat from DC to 250 cps with a sharp cut off. The gain of the amplifier was variable depending upon the ground noise. The tapes were reproduced by pen galvanometers of natural frequency 30 cps with a paper speed of 30 mm/sec.

The period of observation and the number of micro-earthquakes recorded at Suzaka and Matsushiro are given in Table I.

During the period of observation at Matsushiro approximately 2 earthquakes were recorded per minute.

3. – Calculation of Magnitudes of Micro-Earthquakes.

The calculation of magnitude of micro-earthquakes is based on the consideration of attenuation of seismic waves with the epicentral distance.

Muramatu et al ([6]), derived the following equation for calculating the magnitude from the observations of micro-earthquakes in the vicinity of Gifu prefecture.

$$M = 1.25 \log A_v \,(\text{kine}) + 2.5 \log \tau \,(\text{km}) + 1.0 \qquad [1]$$

where A_v is the velocity amplitude and τ is the hypocentral distance. Recently Terashima ([7]) derived the following equation for the calculation of magnitudes of micro-earthquakes.

$$M = \log A_v(\tau) + 1.5 \log \tau + 2.35 \;. \qquad [2]$$

We have used equation [2] in the present study for the calculation of magnitudes of micro-earthquakes.

Substituting the instrumental constants and the hypocentral distances in equation [2] we get:

$M = -\,0.44 + \log A$ For Suzaka monitoring recorder sensitivity, 20mm/mVolt [3]

$M = -0.84 + \log A$ For Suzaka monitoring recorder sensitivity, 50mm/m Volt [4]

$M = -3.19 + \log A$ For Matsushiro monitoring recorder sensitivity, 2mm/m Volt [5]

where A is the double amplitude as measured on the seismograms.

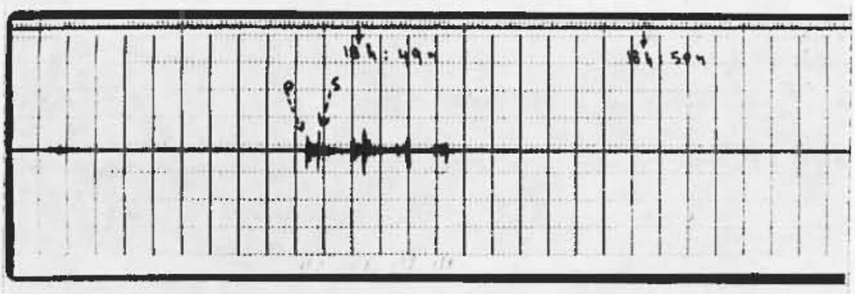

Fig. 2 – Micro-earthquakes recorded at Suzaka on Jan. 14, 1966.

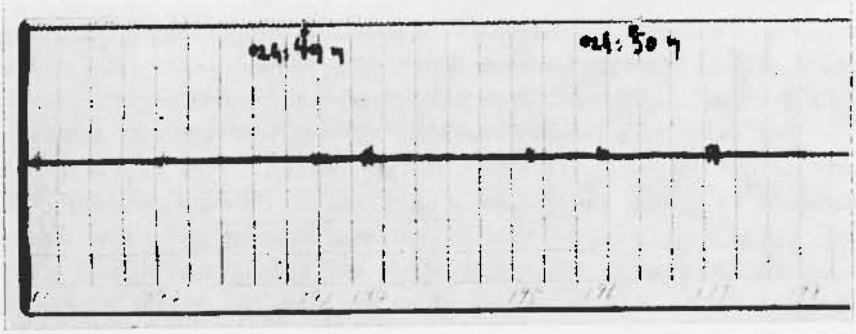

Fig. 3 – Micro-earthquakes recorded at Matsushiro on May 21, 1966.

All the earthquakes of trace amplitude greater than 1 mm recorded on seismograms were utilized for calculating the magnitudes of micro-earthquakes. The earthquakes of magnitude larger than that corresponding to the trace amplitude of 50 mm had to be omitted as the deflections were too large to be within the recording paper.

The duration of P and S interval at Suzaka was approximately 2 seconds. P and S phases were not quite clear at Matsushiro due to the location of the seismometers in the epicentral region. Typical micro-earthquakes recorded at Suzaka and Matsushiro are shown in Figures 2 and 3 respectively.

4. – Results and Discussion.

It is well known that the number N of earthquakes during an arbitrary interval of time in a given seismic region is related to magnitude M by

$$\log N = A' - bM \,. \qquad [6]$$

Many investigators use this equation in the form,

$$\log N = A'' + b\,(8 - M) \,. \qquad [7]$$

In the above equations the constants A', A'' and b are coefficients which are determined from the data by the least square method and the variances are also given.

The values of A' or A'' vary with the duration of time of the data, geographical location and choice of ΔM. The value of b is relatively uniform. However, considerable difference of opinion exists regarding the variations of b with the focal depth, geographical location, foreshock and aftershock sequences, earthquake swarms and volcanic earthquakes.

The value of b increases as the degree of heterogeneity increases and as the degree of symmetry of the applied stress decreases. A decrease of b with depth has been found by several seismologists.

It has been found (8, 9) that the values of b are larger for aftershocks than for foreshocks. The constants b_f and b_a of the fore- and aftershock sequences of the same main shock are connected by the relation(9)

$$b_f = (0.11 \pm 0.13) + (0.65 \pm 0.11)\, b_a \,. \qquad [8]$$

Mogi (10) showed experimentally that when foreshocks and aftershocks occur in the same volume the value b is smaller for foreshocks than for aftershocks because the main shock causes new cracks and thus the number of irregular points increases. The value b for earthquake swarms is larger than for aftershocks or normal seismic activity.

Ishimoto and Iida (4) proposed a formula

$$N(A)\, dA = k\, A^{-m}\, dA \qquad [9]$$

where N is the number of earthquakes and A is the maximum trace amplitude. The coefficients k and m are determined by the least square method. For A, it is sufficient to consider the maximum trace amplitude of an arbitrary chosen standard seismograph. Corrections for distance must be made from the point of observation to the epicentral area.

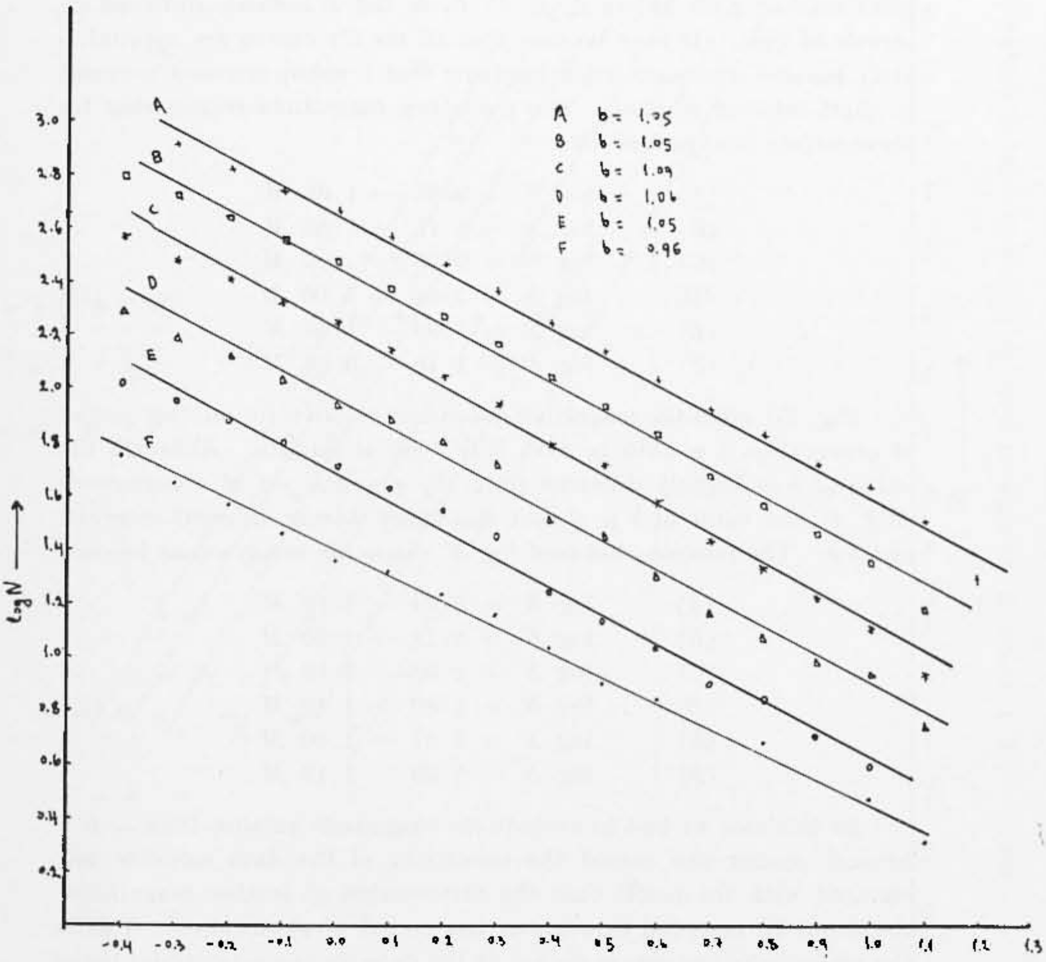

Fig. 4 – log N versus M for different intervals of time recorded at Suzaka (1965).

Since $M \simeq \log A$ for epicentral distance equal to 100 km and $dA = A dM$ it can be shown that the constants b and m in the formulas [6] and [9] are related by

$$b = m - 1 . \qquad [10]$$

The logarithm of the cumulative frequency function $N(M)$ and the magnitude of micro-earthquake recorded at Suzaka during the period 20th to 26th December 1965 is shown in the Fig. 4. The plots marked with letters A, B, C, D, E and F indicate different intervals of time. It may be seen that all the six curves are approximately parallel with each other implying that b values remains constant in short interval of time. The frequency magnitude relationship for these curves is expressed by

$$\begin{array}{ll} (A) & \log N = 2.65 - 1.05\, M \\ (B) & \log N = 2.46 - 1.05\, M \\ (C) & \log N = 2.23 - 1.09\, M \\ (D) & \log N = 1.96 - 1.06\, M \\ (E) & \log N = 1.69 - 1.05\, M \\ (F) & \log N = 1.40 - 0.96\, M . \end{array} \qquad [11]$$

Fig. (5) gives the magnitude-frequency relation for another period of observation i. e. 13th to 14th May 1966 at Suzaka. Although the value of b is slightly different from the previous set of observations (Fig. 4), the value of b is almost stationary during different intervals of time. The relations between log N versus M are given as follows:

$$\begin{array}{ll} (A) & \log N = 2.29 - 1.19\, M \\ (B) & \log N = 2.18 - 1.20\, M \\ (C) & \log N = 2.02 - 1.19\, M \\ (D) & \log N = 1.80 - 1.18\, M \\ (E) & \log N = 1.57 - 1.16\, M \\ (F) & \log N = 1.39 - 1.13\, M . \end{array} \qquad [12]$$

In this case we had to exclude the magnitude smaller than -0.5 because during this period the sensitivity of the data recorder was changed with the result that the earthquakes of smaller magnitudes could not be recorded throughout the period of observation. This is the reason why the curves do not fit the data for the magnitudes lower than -0.5.

The plot of log N versus M at Matsushiro is given in Fig. 6. The value of b remains stationary during different intervals of time

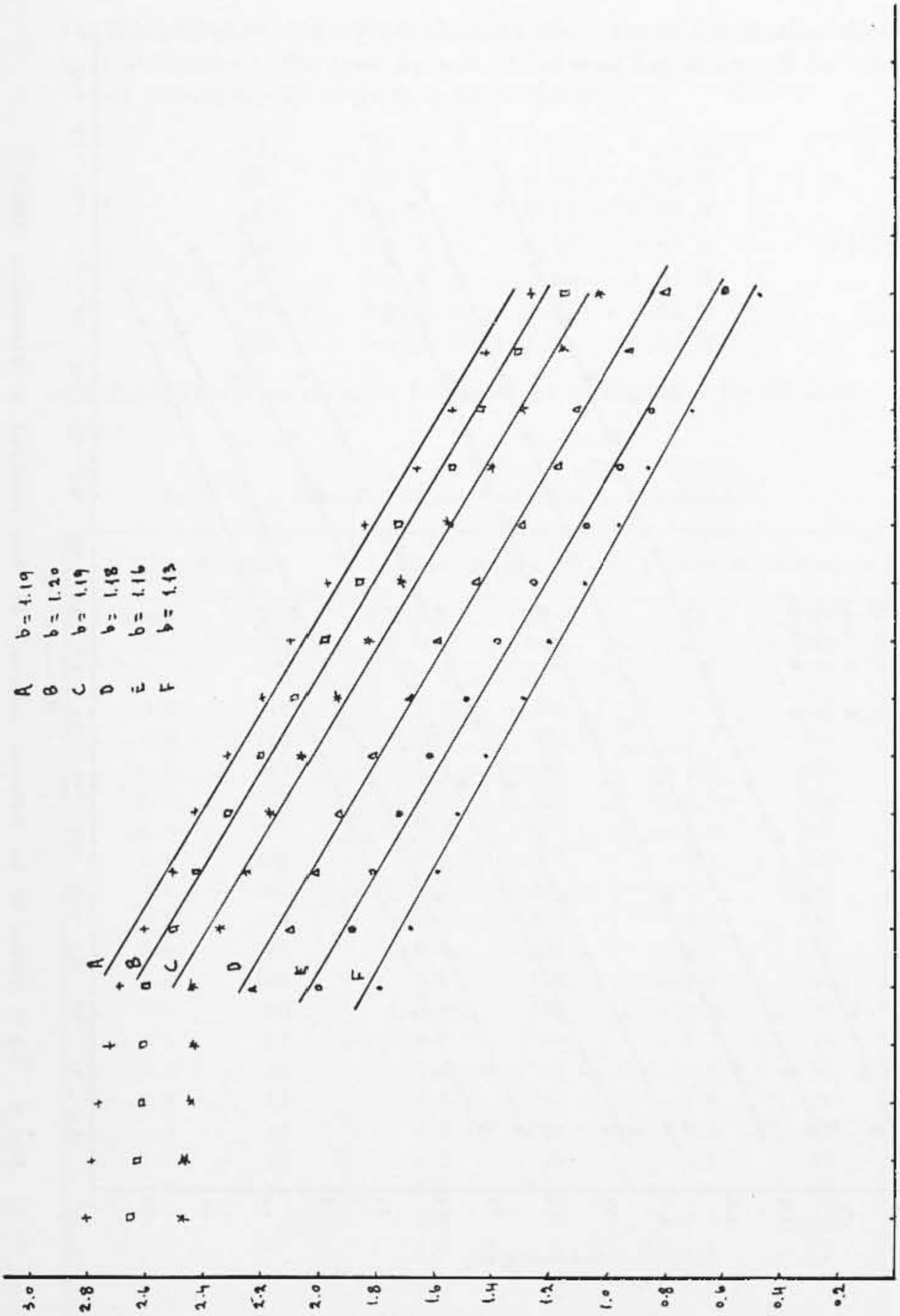

Fig. 5 – log N versus M for different intervals of time recorded at Suzaka (1966).

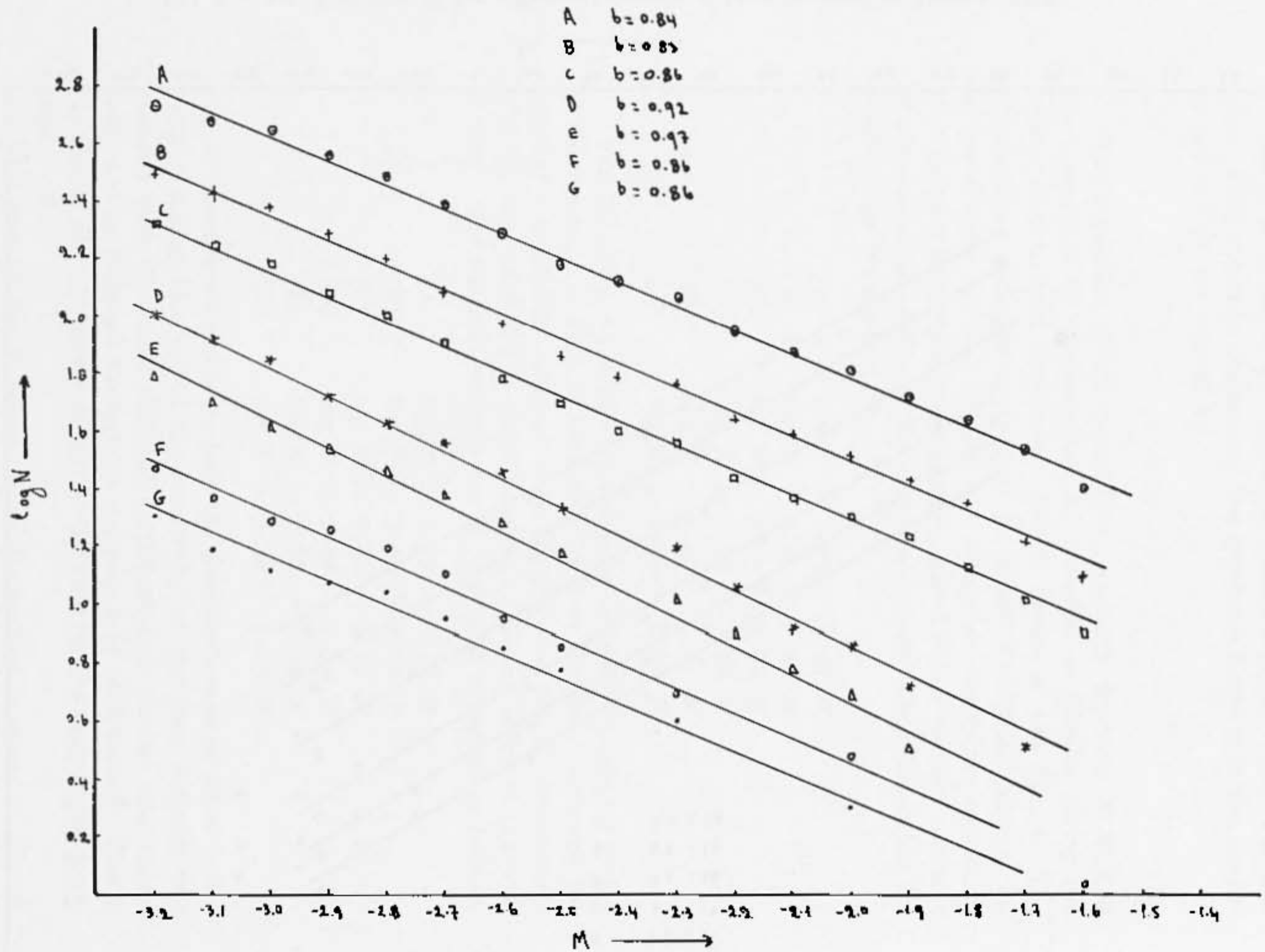

Fig. 6 – log N versus M for different intervals of time recorded at Matsushiro (1966).

for this period of observation although the value of b is smaller than that at Suzaka. The least squares fit between log N and M for different time intervals (Fig. 6) is given below:

$$
\begin{aligned}
&(A) \quad \log N = -0.10 - 0.84\,M \\
&(B) \quad \log N = -0.16 - 0.83\,M \\
&(C) \quad \log N = -0.44 - 0.86\,M \\
&(D) \quad \log N = -0.57 - 0.92\,M \\
&(E) \quad \log N = -0.88 - 0.97\,M \\
&(F) \quad \log N = -1.27 - 0.86\,M \\
&(G) \quad \log N = -1.38 - 0.86\,M\,.
\end{aligned}
\qquad [13]
$$

In Table II the cumulative frequency of earthquakes for all cases is given.

Table II – Cumulative frequency of Earthquakes

From Suzaka I		From Suzaka II		From Matsushiro	
Mag. M	Cum. freq.	Mag. M	Cum. freq.	Mag. M	Cum. freq.
—0.4	849	—0.8	610	—3.2	510
—0.3	742	—0.7	578	—3.1	467
—0.2	649	—0.6	545	—3.0	436
—0.1	555	—0.5	522	—2.9	359
0.0	458	—0.4	478	—2.8	296
0.1	370	—0.3	377	—2.7	237
0.2	297	—0.2	320	—2.6	186
0.3	235	—0.1	261	—2.5	147
0.4	176	0.0	204	—2.4	128
0.5	136	0.1	158	—2.3	114
0.6	108	0.2	130	—2.2	87
0.7	83	0.3	98	—2.1	73
0.8	70	0.4	69	—2.0	63
0.9	53	0.5	45	—1.9	51
1.0	46	0.6	35	—1.8	43
1.1	32	0.7	26	—1.7	34
1.2	19	0.8	15	—1.6	24
1.3	5	0.9	7	—1.5	10
		1.0	2	—1.4	2
		1.1	1		

From the above results it may be seen that, the value of b is stationary in short interval of time in earthquake swarms. This result is similar to that obtained for aftershock sequences ([11]). However, in these earthquake swarms, the value of b changes significantly in different months or different period of observation ([2]).

Table III – VALUE OF b

b	m	fore-aftershocks, swarm, normal seismicity	Authors
0.85	1.8	Matsushiro swarm	Hamada & Hagiwara 1966, Pt. 1
	1.8 – 2.3 Feb. to Mar.	»	
	1.4 – 1.6 Apr. to Jun.	»	Hamada & Hagiwara 1966, Pt. 2
	1.8 – 2.4 Jul. to Aug.	»	Hamada & Hagiwara 1966, Pt. 3
0.95–1.40	m 2.1 till Feb. 1966	»	Party for Seismographic Observation (1967)
1.1			Hori (1967)
0.35 0.76		foreshocks' Matsushiro aftershocks	Suyehiro, et al. (1964)
0.55±0.05 1.13±0.04		foreshocks' Chilean aftershocks earthq.	Suyehiro (1966)
0.6 to 1.3		Large earthq. in different seismic regions	Gutenberg & Richter (1954)
constant		ordinary earthquakes and aftershock activity	Suzuki (1959)

In Table III, the values of b and m obtained by different investigators are given for Matsushiro region. It may be seen that the value of b compares well with the earlier workers.

Suyehiro ([1]) noticed a substantial difference between the foreshocks and aftershocks in the b value which was found to be 0.35 for the foreshocks and 0.76 for the aftershocks of a small perceptible earthquake in the Matsushiro region. Compared with them the value of b is larger as is expected for the earthquake swarms and also suggested by the experiments of Mogi ([12]).

If however, the value of b for Matsushiro region during the swarm is compared with that of general seismicity over different places in the world ([13]), it is rather difficult to conclude that the value is highest during the swarm. One of the possible reasons for this discrepancy is attributed to the different graphical and mathematical methods used for determining b values, besides the use of different magnitude scales.

5. – Conclusion.

The above study brings to light the interesting conclusion that in earthquake swarm the value of b remains stationary in a short time interval although it may change over different period of observations.

6. – Acknowledgements.

The authors are grateful to Dr. S. Omote, Acting Director of International Institute of Seismology and Earthquake Engineering, Tokyo, for encouragement and for providing the necessary facilities for the present investigation.

REFERENCES

(1) Syuehiro S., Asada T. & M. Ohtake, *Foreshocks and Aftershocks Accompanying a Perceptible Earthquake in Central Japan*, "Papers Meteor. Geophys. Tokyo", **15**, 71-88, (1964).

(2) Hamada K & T. Hagiwara, *High Sensitivity Tripartite Observation of Matsushiro Earthquakes*, "Bull. Earthq. Res. Inst." Part 1, 1213-1238, Part 2, 1239-1266, Part 3, 1667-1687, (1966), Part 4, 159-196 (1967).

(3) Gutenberg B. & C. Richter, *Seismicity of the Earth and Associated Phenomena* "Princeton University Press", (1965).

(4) Ishimoto M. & Iida K., *Observations sur les Séismes Enregistrés par le Microseismographe Construit Derniérement* "Bull. Earthq. Res. Inst.", **17**, 443-478, (1939).

(5) *Party for Seismographic Observation of Matsushiro Earthquakes and Seismometrical Section, Matsushiro Earthquakes Observed with a Temporary Seismographic Network*, Part 4, **45**, 887-917, (1967).

(6) MURAMATU I., et al. *Observation of Micro-earthquakes in Mino district in Gifu Prefecture, Central Japan* " J. of Phys. of the Earth ", **11**, 35-49, (1963).

(7) TERASHIMA T., *Magnitude of Micro-earthquake and the Spectra of Micro-earthquake Waves* " Bull. Intern. Inst. Seism. Earthq. Engin ", **5**, 31-108, (1968).

(8) SUYEHIRO S., *Difference between Aftershocks and Foreshocks in the Relationship of Magnitude to Frequency of Occurrence for the Great Chilean Earthquake to 1960* " Bull. Seism. Soc. Am.", **56**, 185-200, (1966).

(9) DRAKOPOULOS J., *Characteristic Parameters of Fore and Aftershock Sequences in the Region of Greece*, " Dissertation in Athens University " (1968).

(10) MOGI K., *Study of Elastic Shocks Caused by the Fracture of Heterogeneous Materials and Its relations to Earthquake Phenomena*, " Bull. Earthq. Res. Inst. ", **40**, 125-174 (1962b).

(11) UTSU T., *On the Nature of Three Alaskan Aftershocks Sequences of 1957 and 1958*, " Bull. Seism. Soc. Am. ", **52**, 279-297 (1962).

(12) MOGI K., *Some Discussions on Aftershocks Foreshocks and Earthquake Swarms – The Fracture of a Semi-Infinite Body Caused by an Inner Stress and Its relation to the Earthquake Phenomena*, " Bull. Earthq. Res. Inst. ", **41**, 615-658, (1963b).

(13) ISACKS B. and OLIVER J., *Seismic Waves with Frequencies from 1 to 100 cycles per second Recorded in a Deep Mine in Northern New Jersey*, " Bull. Seism. Soc. Am. ", **54**, 1941-1979, (1964).

(14) HORI M., *Matsushiro Earthquake Swarm and Its Peripheral Seismicity*, " Bull. Earthq. Res. Inst. ", **45**, 489-503, (1967).

(15) SUZUKI A., *A statistical Study on the Occurrence of Small Earthquakes*, " Sci. Rept. Tohoku Univ., Ser. 5, Geophys. " **11**, 10-54, (1959).