FREQUENCY DISTRIBUTIONS OF EARTHQUAKE INTENSITIES ON OAHU, HAWAII

by
Doak C. Cox
Environmental Center
University of Hawaii

1986

ABSTRACT

The record of intensities of historic earthquakes felt on Oahu compiled in a companion report has been subjected to tests for completeness and for the validity of the intensity estimates. The record from 1859 through 1983 seems to be essentially complete for quakes with Modified Mercalli intensities of V or greater at Honolulu, and that since about 1910 essentially complete for quakes with Honolulu intensities of IV or greater. No evidence of systematic bias of the intensity estimates was found.

A composite record, including all earthquakes with Honolulu intensities of IV or greater occurring during the 74-year period from 1910 through 1983 and the single quake occurring prior to 1910 that had a Honolulu intensity larger than any in the 74-year period, was subjected to frequency analysis. Frequency distributions of both exponential form and of power-law form were found to fit the composite record well. From these frequency distributions, it is estimated that the return interval for earthquakes with intensities of VII or greater in Honolulu lies almost certainly between 74 and 255 years and probably between 125 and 158 years. The records of intensities at places in the western part of Oahu are much less complete, but it appears that, at those places, the return intervals for earthquakes of VII or greater are probably between 480 and 610 years.

CONTENTS

TABLES

FIGURES

INTRODUCTION

Purpose and nature of study

This report is one of several associated with an investigation of the seismic risk zone to which Oahu should appropriately be assigned in the building code of the City and County of Honolulu. The principal basis of that code is the Uniform Building Code (UBC), published by the International Conference of Building Officials (1979), in which the only quantitative criteria used to discriminate among seismic risk zones are earthquake intensities in the Modified Mercalli intensity scale of 1931 (Wood and Neumann, 1931). If the seismic risk zone to which Oahu should be assigned were to be based on the greatest earthquake intensity known to have been experienced on the island, the investigation could have been restricted to identifying the earthquake with the highest Oahu intensity occurring since 1859, the year of the earliest datable earthquake felt on the island. Presumably, however, the risk zone assignment should be based on the expectable future intensity associated with some fairly low average recurrence frequency.

It is expectable that the average recurrence frequencies of earthquakes in the future will be inversely related to their intensities as it has been in the past. Even to estimate the average recurrence frequency of the greatest earthquake intensity in the historic record of an area, it is necessary to estimate the frequency distribution of earthquake intensities in the area. Hence one of the principal needs in the overall investigation, and that addressed in the study reported here, was the estimation of the frequency distributions of average earthquake intensities in areas of Oahu. Such frequency distributions must be based on historical records. The study therefore included the compilation of a record of earthquakes felt on Oahu, the compilation of information on the effects that those earthquakes had on the island, the estimation of their intensities at various places from those effects, and the estimation of the frequency distributions of the average intensities at those places.

The development of the list of earthquakes felt on Oahu, descriptions of the Oahu effects of those earthquakes, and estimates of the intensities of the earthquakes derived from their effects have been or are being published separately (Cox, 1985a, 1986a, and 1986b). This report deals with tests of the historical record and with the determination of frequency distributions of the Oahu intensities. The implications of the frequency distributions with respect to seismic risk zoning on Oahu will be dealt with in a subsequent report by a task force appointed for the purpose by the Natural Hazards Group of the University of Hawaii (Berg *et al.*, in prep.).

Intensities, magnitudes, dates, times, and places

Intensities

The intensity scales used in this report are versions of the Modified Mercalli (MM) scale of 1931. Intensity values expressed in roman numerals are those in the original discrete-step version of the scale (Wood and Neumann, 1931; Table A-1 in Cox, 1986b) or the 1936 version that reflects better the influence of type of masonry on the effects of earthquakes on masonry structures (Richter, 1958; Table

A-3 in Cox, 1986b). Intensity values expressed in arabic numerals with decimals are those in an equivalent continuous scale whose values, if rounded to the nearest integer, are identical to corresponding values in the conventional scale (Cox, 1985b) so that:

$$I - 0.5 \lesssim I' \lesssim I + 0.5$$

where I = MM intensity, discrete-step scale

I' = MM intensity, continuous scale

The intensity estimates in the record of earthquakes felt on Oahu published in the companion report (Cox, in press a) are intended to be event and place-specific averages. To each average is attached an estimate of the possible error in its estimation, the errors being assumed greatest for event-place combinations for which there are few reports of effects or greater than normal inconsistencies among the intensities implied by the reports.

Magnitudes

Most of the earthquake magnitudes referred to in this report are Richter magnitudes. For those earthquakes for which Richter magnitudes, as such, have not been reported, the nearest equivalents are used (generally M_S or M_L rather than m_b).

Dates and times

The date and time of occurrence of an earthquake is of no significance in the estimation of its intensity. However, event-date-time errors, if not recognized and rectified, may result in an estimate of the number of earthquakes differing substantially from the number of earthquakes that actually occurred. Hence considerable effort was made in the compilation of the record of earthquakes felt on Oahu to determine the actual date and time of occurrence of each quake and to eliminate duplications of events.

The local and standard times used in this report and their relation to Greenwich Mean Time (GMT) are, for events occurring:

Through Dec 1895: Honolulu local time = GMT - 10 hr. 31 min.

Jan 1886 through Jan 1941: Hawaiian Standard Time (HST) = GMT - 10 hr. 30 min.

Feb 1941 through Sep 1945: Hawaiian War Time (HWT) = GMT - 9 hr. 30 min.

Oct 1945 to date: Hawaiian Standard Time (HST) = GMT - 10 hr.

Places

The locations of places on Oahu for which there are available descriptions of the effects of earthquakes are shown on maps in the companion report (Figures 1 and 2 in Cox, 1986b).

In the case of those earthquakes for which it is possible to estimate intensities at places other than Honolulu, the estimates have been grouped for statistical purposes as they relate to the Kailua-Waimanalo area, the Kaneohe area, the central part of the island (Wahiawa, Schofield Barracks, Wheeler Air Force Base, and Kunia), the Pearl Harbor area, the Waianae coast, the Waialua area, and the north-shore area (Figure 1).

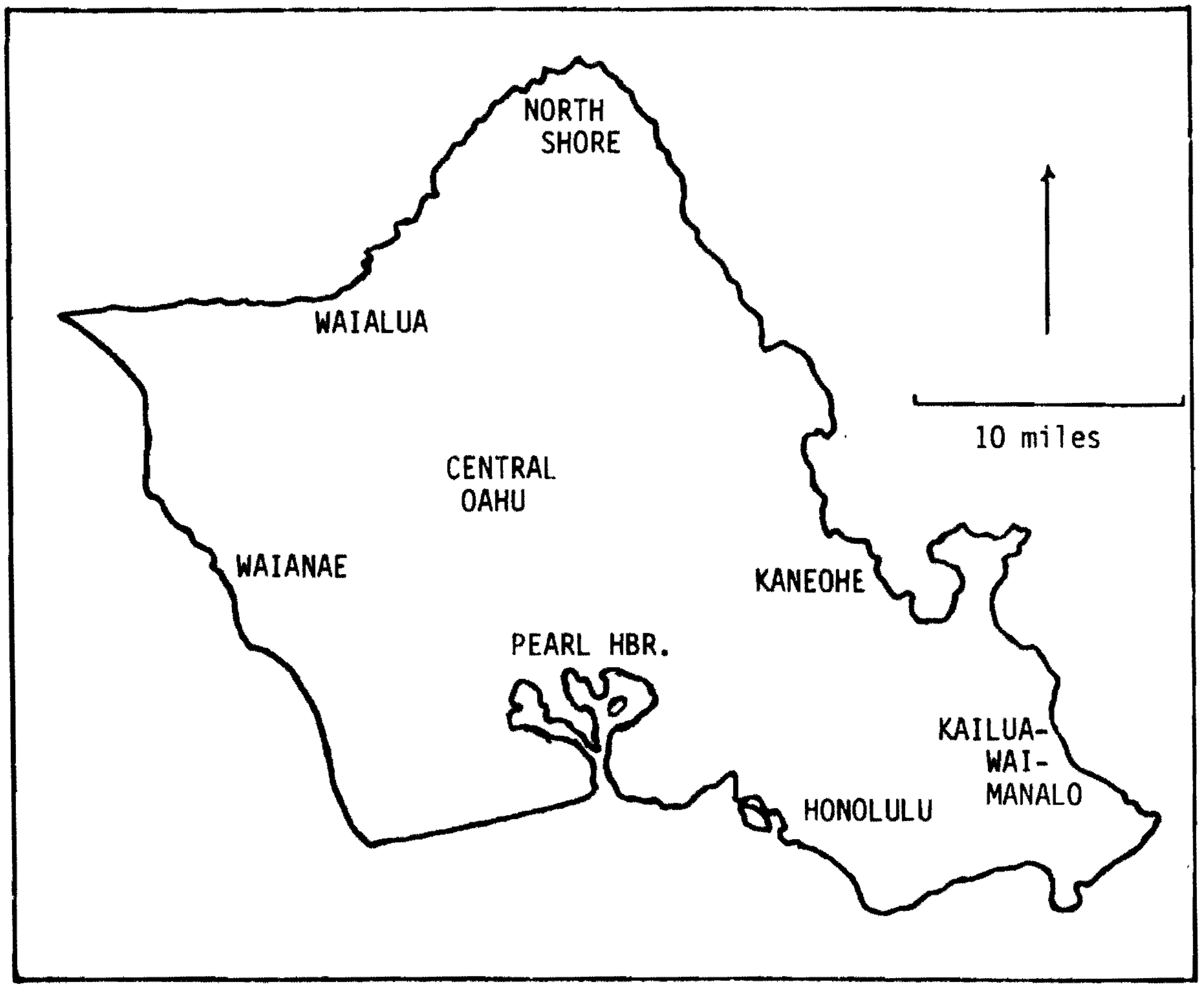

Figure 1. Location map, areas of Oahu.

RECORD OF EARTHQUAKES FELT ON OAHU AND TESTS

The record

The earliest earthquake known to have been felt on Oahu occurred in 1859. Of 139 events reported in various sources as if earthquakes felt on Oahu from 1859 through 1983, 26 were found in the study not to have been natural earthquakes actually felt on the island. The dates and times of the 113 natural earthquakes actually felt on Oahu, the locations of their hypocenters, their magnitudes, and their Honolulu intensities, as estimated in the study, are listed in Table 1.

In the case of the 73 earthquakes for which epicenters have been estimated, either from seismographic evidence or from distributions of reported effects, the epicenters are plotted in Figure 2, using symbols differentiating the quakes by both magnitude and Honolulu intensity.

The intensities of the quakes at places on Oahu other than Honolulu are listed in Table 2 in the case of the 40 quakes for which such intensities have been estimated.

Tests of intensity record

In preparation for or in conjunction with the use of the record of intensities estimated in this study in frequency analyses, the record was subjected to several tests intended to determine its reliability.

Comparison of intensity estimates with previous estimates

To investigate the possibility of bias in the estimation of intensities in this study, the estimates were compared with estimates that had been published previously in various reports for 18 of the earthquakes at one or more places. The results are displayed as a scatter diagram in Figure 3. The previous values indicated by the plotting of most of the points correspond to the integer values of the conventional MM scale. However, in the case of a value read from an intensity distribution map for a place at or very close to the boundary between two conventionally mapped "isointensity" zones, or one translated from a Rossi-Forel intensity equivalent to parts of two Modified Mercalli intensity ranges, the point has been plotted midway betwen the two conventional MM integer value. For a place within which there were several sites with previously estimated intensities, the point plotted represents the average of the previous estimates.

If the values previously estimated and the corresponding values estimated in this study had been identical, the points would have fallen on the dashed line shown on the figure. That there should be a considerable scatter of the points about that line is not surprising. Between intensity estimates for the same event and place there may be differences stemming from: i) differences in the records of effects on which the estimates were based; ii) differences in generality with respect to the area intended to be represented by the estimates; and iii) differences in the judgments of the estimators. Differences in judgment no doubt contribute to all of the differences between the previous and new estimates, and the other sources of difference are clearly involved in some cases. However, the figure suggests that any systematic bias on the estimates made in the study is very small.

Table 1. Historic earthquakes felt on Oahu and their Honolulu intensities (I′).

No.	Year	Honolulu Mo Day Time	Greenwich Mo Day Time	Hypocenter Lat. °	Long. °	H km.	Mag	Honolulu intensity Av.	+/-
1	1859	NOV 21 02:25	NOV 21 12:56	Hawaii vic.?				3.8	1.0
2	1861	DEC 5 11:49	DEC 5 22:20	Molokai-Lanai vic.(?)				5.0	1.0
3	1861	DEC 15 19:21	DEC 16 05:52	Event 2 vic.				4.8	1.0
4	1868	APR 2 15:53	APR 3 02:24	19.2	155.3		7.5	4.5	1.0
5	1868	APR 4 00:27	APR 4 10:58	NW of event 4				4.6	1.0
6	1868	APR 4 00:48	APR 4 11:19	Event 4 vic.				3.0	1.0
7	1868	APR 4 01:00	APR 4 11:31	NW of event 4				2.0	1.0
8	1868	APR 4 03:02	APR 4 13:33	NW of event 4				3.5	1.0
9	1869	JAN 18 17:30	JAN 19 04:01	NE Oahu vic.				2.8	1.0
10	1871	FEB 19 22:11	FEB 19 08:41	20.7	157.0		7.0	6.5	.7
11	1871	FEB 20 21:00	FEB 21 07:31	Event 10 vic.				2.0	1.0
12	1871	FEB 24		Event 10 vic.				2.0	1.0
13	1871	MAR 3 23:45	MAR 4 10:16	Event 10 vic.				2.2	1.0
14	1881	APR 21 14:20	APR 22 01:01	Maui group vic.				3.0	1.0
15	1881	SEP 30 04:53	SEP 30 15:24	Hawaii vic.				4.2	.8
16	1881	SEP 30 04:58	SEP 30 15:29	Event 15 vic.				2.0	1.5
17	1885	JAN 12 20:00	JAN 13 06:31	Event 18 vic.				1.3	1.0
18	1885	JAN 13 05:59	JAN 13 16:30	Maui vic.				4.2	.5
19	1895	DEC 8 23:04	DEC 9 09:04	Oahu vic.				5.0	.8
20	1895	DEC 9 03:06	DEC 9 13:36	Event 19 vic.				1.5	1.0
21	1908	SEP 20 20:12	SEP 21 06:22	19.5	155.4		6.2	2.5	1.0
22	1912	OCT 13 05:48	OCT 13 16:18	Hawaii vic.				4.0	.8
23	1919	JAN 28 16:53	JAN 29 03:23	W Molokai vic.				2.5	1.0
24	1923	JAN 14 02:25	JAN 14 12:55	Event 25 vic.				1.5	1.0
25	1923	JAN 14 02:28	JAN 14 12:58	Hawaii vic.				4.0	.7
26	1923	DEC 25 18:46	DEC 26 05:16	Oahu-Lanai-Molo.vic.				4.0	.7
27	1925	JUL 29 21:19	JUL 30 07:49	Oahu vic.				2.5	1.0
28	1926	FEB 7 11:29	FEB 7 21:59	Maui-Hawaii vic.				3.0	1.0
29	1926	MAR 19 22:33	MAR 20 09:03	20.5	155.5			4.5	.5
30	1927	MAR 20 04:51	MAR 20 15:21	20.0	157.0			4.3	.7
31	1927	AUG 3 09:42	AUG 3 20:12	Hawaii				1.4	1.0
32	1929	OCT 5 21:22	OCT 6 07:52	19.8	156.0		6.5	4.7	.7
33	1932	JUL 7 22:31	JUL 8 08:31	19.4	155.4	10		1.3	.8
34	1934	SEP 5 18:35	SEP 6 05:05	Oahu vic.				3.5	1.0
35	1935	NOV 21 01:11	NOV 21 11:41	19.5	155.5	<8		2.5	1.0
36	1936	MAY 11 17:45	MAY 12 04:15	Oahu vic.				1.3	.8
37	1936	AUG 16 07:38	AUG 16 18:08	Oahu vic.				1.8	.8
38	1938	JAN 22 22:03	JAN 23 08:33	21.2	156.1		6.8	5.5	.5
39	1938	MAR 3 15:00	MAR 4 01:30	Event 38 vic.				2.0	1.0
40	1938	MAR 21 17:30	MAR 22 04:00	Event 38 vic.				1.0	1.0

Table 1. (Continued).

No.	Year	Honolulu Mo	Honolulu Day	Honolulu Time	Greenwich Mo	Greenwich Day	Greenwich Time	Hypocenter Lat. o	Hypocenter Long. o	Hypocenter H km.	Mag	Honolulu intensity Av.	Honolulu intensity +/-
41	1939	MAY	13	15:32	MAY	14	02:02	Oahu vic.				1.3	1.0
42	1939	MAY	24	23:59	MAY	24	10:29	19.4	155.2			1.3	1.0
43	1939	MAY	29	19:15	MAY	30	29:45	19.5	156.8			3.5	.7
44	1940	JUN	16	23:57	JUN	17	10:27	21.0	155.3		6.0	4.0	1.0
45	1940	JUN	17	07:47	JUN	17	18:17	20.5	155.2			1.7	1.0
46	1940	JUN	17	12:39	JUN	17	23:09	21.0	155.2			1.0	1.0
47	1940	JUL	15	16:48	JUL	16	03:18	20.9	155.1		5.5	1.2	1.0
48	1941	SEP	25	07:19	SEP	25	17:49	19.5	155.5	11	6.0	2.4	1.0
49	1944	DEC	27	04:42	DEC	27	14:12	19.5	155.5		5.5	3.8	1.0
50	1945	MAY	19	02:48	MAY	19	12:18	19.3	155.5	22		3.7	1.0
51	1948	JAN	17	19:32	JAN	18	05:32	Event 52 vic.				3.5	1.0
52	1948	JUN	28	01:41	JUN	28	11:41	21.2	157.9		4.6	6.0	.7
53	1948	JUN	28	01:51	JUN	28	11:51	Event 52 vic.				2.0	2.0
54	1951	APR	22	14:52	APR	23	00:52	19.4	155.2	44	6.2	4.0	1.0
55	1951	AUG	21	00:57	AUG	21	10:57	19.5	156.0		6.9	4.0	1.0
56	1951	DEC	12	13:18	DEC	12	23:18	Diamond Hd.-Koko Hd.				2.0	1.0
57	1951	DEC	12	13:21	DEC	12	23:21	Diamond Hd.-Koko Hd.				2.0	1.0
58	1952	APR	6	21:10	APR	7	07:10	21.0	157.0	60		4.0	.5
59	1952	DEC	8					Oahu vic.				1.8	1.0
60	1953	JAN	15	02:05	JAN	15	12:05	19.3	155.3	24	5.2	4.0	1.0
61	1953	AUG	21	19:47	AUG	22	05:47	19.7	155.7			2.2	1.0
62	1954	MAR	30	08:42	MAR	30	18;42	20.0	155.0	24	6.5	2.0	1.0
63	1955	APR	1	04:24	APR	1	14:24	19.5	155.0	10		2.0	1.0
64	1955	AUG	7	07:18	AUG	7	17:18	20.5	155.5	40		2.0	1.5
65	1955	AUG	14	02:28	AUG	14	12:28	19.5	155.5	25		2.2	1.0
66	1955	NOV	22	20:43	NOV	23	06:43	NE Oahu vic.				1.5	1.2
67	1955	DEC	26	14:24	DEC	27	00:24	N coast Molokai				2.0	1.0
68	1956	FEB	18	17:04	FEB	19	03:04	SE Oahu vic.				1.8	1.0
69	1956	MAY	13	21:54	MAY	14	07:54	20.3	155.3	20		2.0	1.0
70	1956	AUG	7	07:05	AUG	7	17:05	21.2	157.4	24		3.0	1.0
71	1956	OCT	16	00:45	OCT	16	10:45	19.8	156.5			4.0	1.0
72	1957	AUG	18	00:42	AUG	18	10:42	21.0	156.0	10	5.6	3.0	1.0
73	1958	FEB	23	04:01	FEB	23	14:01	21.5	157.8	sh	3.7	3.0	1.0
74	1959	OCT	21	03:10	OCT	21	13:10	21.7	157.6		3.5	3.0	1.0
75	1960	SEP	13	05:35	SEP	13	15:35	21.5	157.5			1.8	1.8
76	1960	SEP	26	04:25	SEP	26	14:25	21.5	157.5			1.5	1.5
77	1961	JUL	23	05:24	JUL	23	15:24	19.5	155.2	44	5.0	4.0	1.0
78	1961	JUL	23	05:28	JUL	23	15:28	19.5	155.2	44	4.7	2.0	1.0
79	1962	JUN	27	18:27	JUN	28	04:27	19.4	155.4	5	6.1	1.5	1.5
80	1963	JAN	8	09:40	JAN	8	19:40	19.4	155.3	30	4.3	1.3	1.3

Table 1. (Continued).

No.	Year	Honolulu Mo Day Time	Greenwich Mo Day Time	Hypocenter Lat. o	Long. o	H km.	Mag	Honolulu intensity Av.	+/-
81	1963	AUG 14 05:26	AUG 14 15:26	21.5	158.1	30	3.5	2.0	1.5
82	1964	OCT 11 00:07	OCT 11 10:07	18.8	155.6	13	5.5	4.5	1.0
83	1964	DEC 2 22:21	DEC 3 08:21	19.6	155.3	30	4.7	4.0	.8
84	1967	NOV 3 00:53	NOV 3 10:53	19.8	156.8	13	4.1	2.0	1.5
85	1969	MAY 24 16:38	MAY 25 02:38	21.2	157.7	33	3.6	2.0	.8
86	1969	SEP 3 09:40	SEP 3 19:40	19.3	155.4	31	4.3	2.0	1.0
87	1971	APR 25 23:56	APR 26 09:56	19.4	156.3	22	4.5	1.0	1.0
88	1972	FEB 29 12:08	FEB 29 22:08	19.4	156.3	19	5.0	1.2	1.2
89	1972	DEC 23 09:05	DEC 23 19:05	19.6	156.0	45	5.2	3.5	1.0
90	1972	DEC 24 10:43	DEC 24 20:43	19.6	156.0	47	4.8	1.5	1.5
91	1973	APR 26 10:26	APR 26 20:26	19.9	155.1	45	6.2	5.0	.5
92	1974	DEC 25 07:48	DEC 25 17:48	20.3	155.6	28	4.7	1.0	1.0
93	1975	MAY 21 22:33	MAY 22 08:33	19.3	155.0			1.0	1.0
94	1975	NOV 29 04:48	NOV 29 14:48	19.3	155.0	8	7.2	4.0	1.0
95	1976	JAN 15 10:01	JAN 15 20:01	Oahu vic.				2.8	1.0
96	1976	JAN 22		Oahu vic.				3.8	1.0
97	1976	FEB 20 19:51	FEB 21 05:51	20.4	156.3	33	5.1	2.0	1.0
98	1976	MAY 23 23:24	MAY 24 09:24	20.8	156.2	0	4.1	3.0	1.0
99	1977	SEP 5 09:40	SEP 5 19:40	21.4	157.5	10	3.5	1.5	1.2
100	1978	OCT 28 12:38	OCT 28 22:38	21.6	158.0	5	4.2	3.4	.8
101	1979	JAN 1 20:31	JAN 2 06:31	21.0	156.1	12	3.5	1.5	.8
102	1979	MAR 6 05:08	MAR 6 15:08	19.5	155.3	27	4.7	2.0	1.0
103	1979	MAR 29 23:07	MAR 30 09:07	20.6	158.8	19	5.5	4.0	.7
104	1979	AUG 14 02:52	AUG 14 12:52	20.8	156.3	24	4.5	3.5	.8
105	1980	JUL 4 19:36	JUL 5 05:36	20.9	157.8	10	3.7	2.5	1.0
106	1980	NOV 11 00:51	NOV 11 10:51	Event 107 vic.				1.5	1.0
107	1980	NOV 12 11:38	NOV 12 21:38	21.5	158.3	14	4.0	2.0	1.0
108	1981	JAN 12 04:18	JAN 12 14:18	19.4	155.4		4.3	2.0	2.0
109	1981	MAR 5 04:10	MAR 5 14:10	21.4	156.8	10	5.0	5.0	.8
110	1981	MAR 5 16:44	MAR 6 02:44	21.7	156.6	10	4.0	2.0	2.0
111	1982	JAN 21 11:53	JAN 21 21:53	19.2	155.7	10	5.4	2.5	1.0
112	1982	JAN 21 12:29	JAN 21 22:29	19.2	155.7	14	5.1	1.5	1.5
113	1983	NOV 16 06:13	NOV 16 16:13	19.4	155.4	7	6.7	2.8	1.0

Table 2. Oahu intensities (I') of historic earthquakes at places other than Honolulu.

No.	Honolulu Date & time Year	Mo	Day	Time	Waimanalo Av.	+/-	Lanikai-Kailua Av.	+/-	Kaneohe Area Av.	+/-	Central Oahu Av.	+/-	Pearl Hbr.Area Av.	+/-	Waianae Area Av.	+/-	Waialua Area Av.	+/-	North Shore Av.	+/-
6	1868	APR	2	15:53					4.5	1.5										
7	1868	APR	4	00:27					4.5	1.5										
8	1868	APR	4	00:48					3.0	1.5										
9	1868	APR	4	01:00					2.0	1.5										
10	1868	APR	4	03:02					3.5	1.5										
11	1869	JAN	18	17:30					3.0	1.0										
12	1871	FEB	19	22:11	6.4	1.0			6.4	1.0			5.8	1.0	5.8	1.0	5.8	1.0		
24	1912	OCT	13	05:48			4.0	.8												
34	1929	OCT	5	21:22	4.7	1.0					3.5	1.0			3.5	1.0			3.0	1.0
40	1938	JAN	22	22:03	5.5	.5	5.5	.5	5.5	.5	5.2	.5	5.2	.5	5.2	.5				
42	1938	MAR	21	17:30									1.5	.8						
54	1948	JUN	28	01:41							5.5	1.0	5.5	1.0						
60	1952	APR	6	21:10					4.0	1.5	4.0	1.5	4.0	1.5						
62	1953	JAN	15	02:05			4.0	1.0	4.0	1.0	4.0	1.0	4.0	1.0	4.0	1.0				
67	1955	AUG	14	02:28			2.2	1.0	2.2	1.0										
68	1955	NOV	22	20:43					2.0	1.0										
69	1955	DEC	26	14:24			2.0	1.0												
72	1956	AUG	7	07:05	4.0	1.0	3.0	1.0					2.0	1.0						
73	1956	OCT	16	00:45			4.0	1.0	4.0	1.0			4.0	1.0						
75	1958	FEB	23	04:01			4.8	1.0	4.8	1.0										
76	1959	OCT	21	03:10	4.5	1.0	4.5	1.0	4.5	1.0										
77	1960	SEP	13	05:35			3.4	1.0												
78	1960	SEP	26	04:25			3.0	1.0												
79	1961	JUL	23	05:24			4.0	1.0												
82	1963	JAN	8	09:40			3.0	2.0												

Table 2. (Continued).

	Honolulu Date & time			Intensities															
				Waimanalo		Lanikai-Kailua		Kaneohe Area		Central Oahu		Pearl Hbr.Area		Waianae Area		Waialua Area		North Shore	
	Year	Mo Day	Time	Av.	+/-	Av.	+/-	Av.	+/-	Av.	+/-	Av.	+/-	Av.	+/-	Av.	+/-	Av.	+/-
83	1963	AUG 14	05:26			2.5	1.0	2.5	1.0					3.0	1.0				
86	1967	NOV 3	00:53			3.0	1.0												
87	1969	MAY 24	16:38			2.0	.8	2.0	.8										
88	1969	SEP 3	09:40			2.0	.8	2.0	.8										
91	1972	DEC 23	09:05			3.5	1.0	3.5	1.0									2.5	1.5
93	1973	APR 26	10:26	4.8	.8	5.0	.8	5.0	.8	4.5	.8	4.5	.8	4.0	.8	4.0	.8	4.0	.8
96	1975	NOV 29	04:48			4.0	1.0					4.0	1.0					4.0	1.0
97	1976	JAN 15	10:01			2.8	1.0	2.8	1.0									2.8	1.0
98	1976	JAN 22				3.8	1.0	3.8	1.0			3.8	1.0						
99	1976	FEB 20	19:51					2.0	1.0										
101	1977	SEP 5	09:40	2.0	.8	2.0	.8	2.0	.8										
102	1978	OCT 28	12:38					3.4	.8	3.6	.8							3.4	.8
103	1979	JAN 1	20:31					2.0	1.0										
105	1979	MAR 29	23:07	4.0	.7	4.0	.7					4.5	1.0	3.5	.8	3.5	.8	3.5	.8
106	1979	AUG 14	02:52									3.5	.8						
107	1980	JUL 4	19:36					2.5	1.0										
108	1980	NOV 11	00:51							2.0	1.0								
109	1980	NOV 12	11:38							3.0	1.0			3.0	1.0	3.0	1.0		

* Times: 1868-1895: Honolulu local time = GMT - 10 hr.,31 min.
1896-1941: Hawaiian Standard Time = GMT - 10 hr.,30 min.
1945-date: Hawaiian Standard Time = GMT - 10 hr.

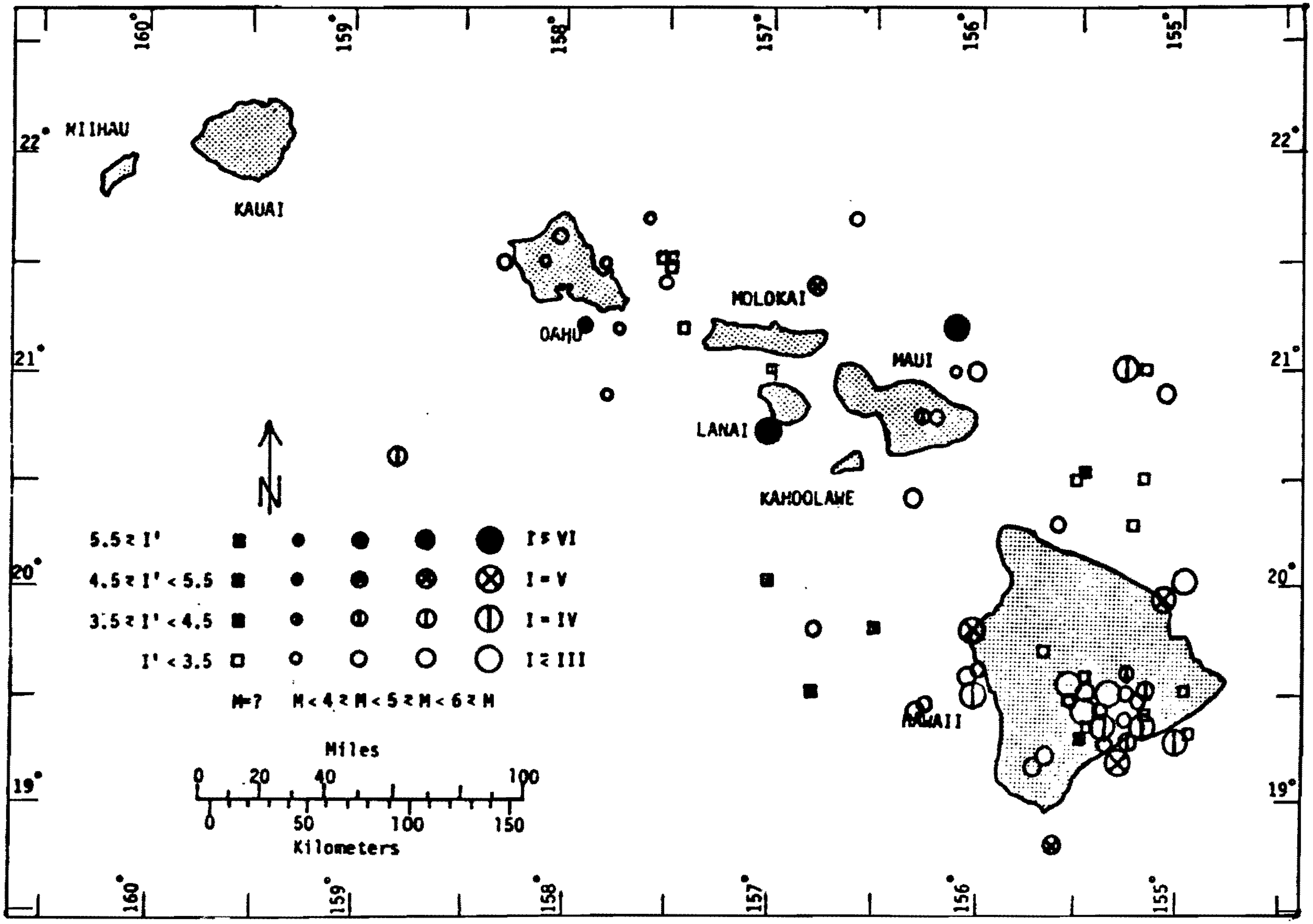

Figure 2. Geographic distribution of epicenters of earthquakes felt on Oahu.

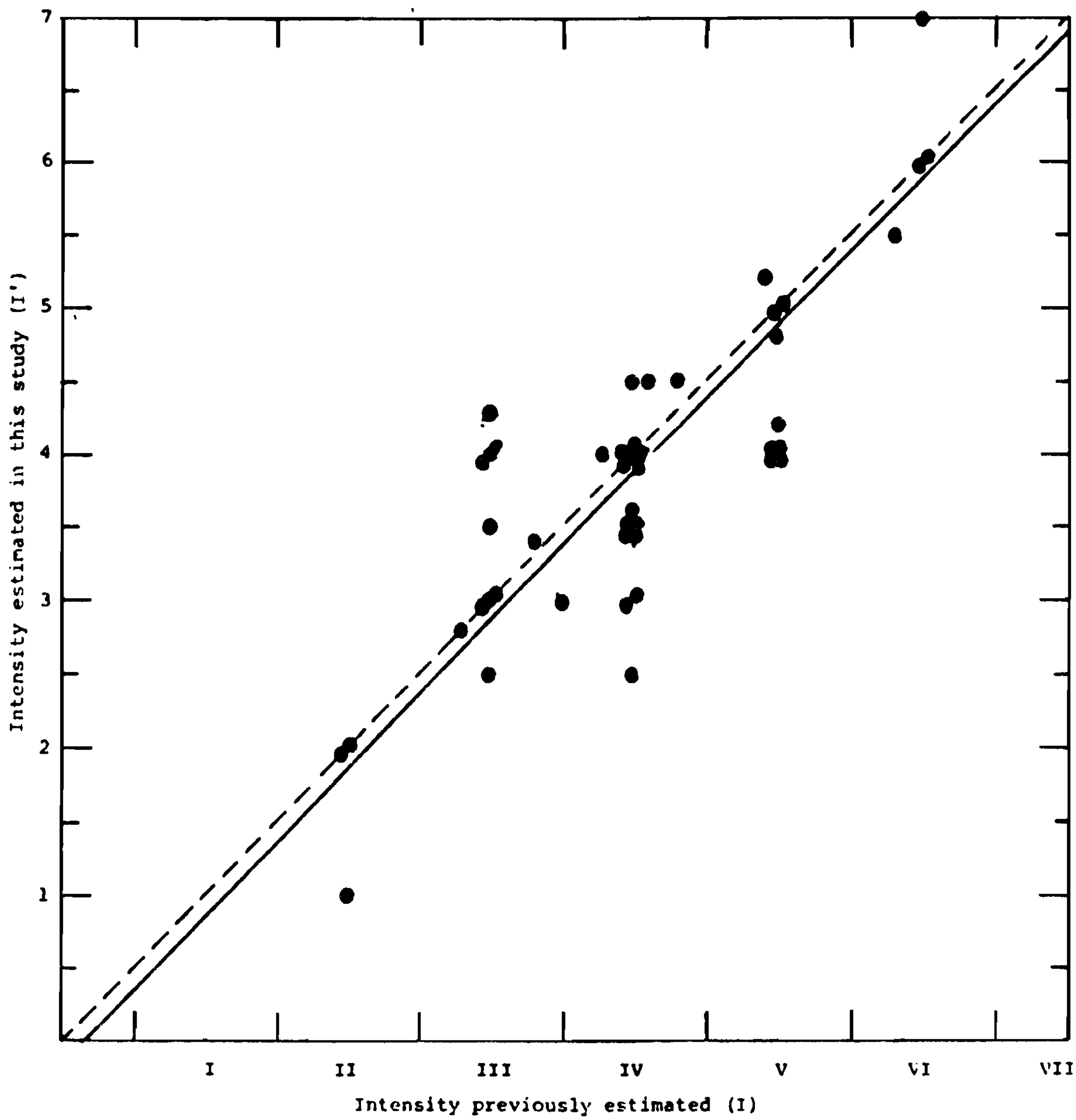

Figure 3. Comparison of Oahu intensities estimated in this study with previous estimates.

The solid line shown in the figure is the mutual regression line representing that correlation between the two sets of estimates that is best in the sense that the mean of the square of normal departures of the points from the line is minimized. The slope of this line is 0.99 and the intercept only 0.14. The correlation coefficient is 0.94.

Comparison of intensity estimates with calculated values

Relationships among intensity, epicentral-area intensity, magnitude, and epicentral or hypocentral distance, determined for earthquakes in the contiguous United States by Howell and Schultz (1975), have been combined and modified for application to Hawaiian earthquakes by Cox (1985b). The result is the relationship:

$$\ln(I'+0.5) = (M-1) + 0.877 - 0.144 \ln r - 0.00053\, r$$

where I' = MM intensity, continuous-scale version

M = Richter magnitude

$r = (x^2 + h^2)^{\frac{1}{2}}$ = hypocentral distance, km.

x = epicentral distance, km.

h = focal depth, km, if known, otherwise 14 km.

For the 50 earthquakes for which Honolulu intensities have been estimated, and for which epicentral locations and magnitudes have either been determined from seismographic information or estimated from intensity distributions, estimates of Honolulu intensity calculated from this relationship are plotted against the estimates based on the effects of the earthquake at Honolulu in Figure 4. If the two sets of estimates had been identical, the points would have lain on the dashed line on the figure.

The solid line shown represents the mutual regression line for the 47 points shown as small solid circles, excluding the three points shown as larger open circles that represent earthquakes whose epicenters and magnitudes were estimated from their intensity distributions. If the relationship on which the calculated values are based were fully reliable, this line would suggest that the estimates based on the earthquake effects were underestimated for intensities less than 4.0 and overestimated for intensities greater than 4.0. However, the mutual line of regression for the points representing quakes with effects-based intensity estimates of $I' \geq 3.0$ would be practically indistinguishable from the dashed line, suggesting that the bias is restricted to the estimates of smaller intensities. The bias, indeed, is at least as likely to represent overestimation of the calculated intensities as underestimation of the effects-based intensities.

Tests for completeness of record

It seemed safe to assume that, in the entire 125-year period since 1859, every quake that had a high intensity on Oahu was included in the record that was used in guiding the search for contemporary descriptions of the effects of the earthquakes. However, because the inclusion of events in the record depended in part on notice

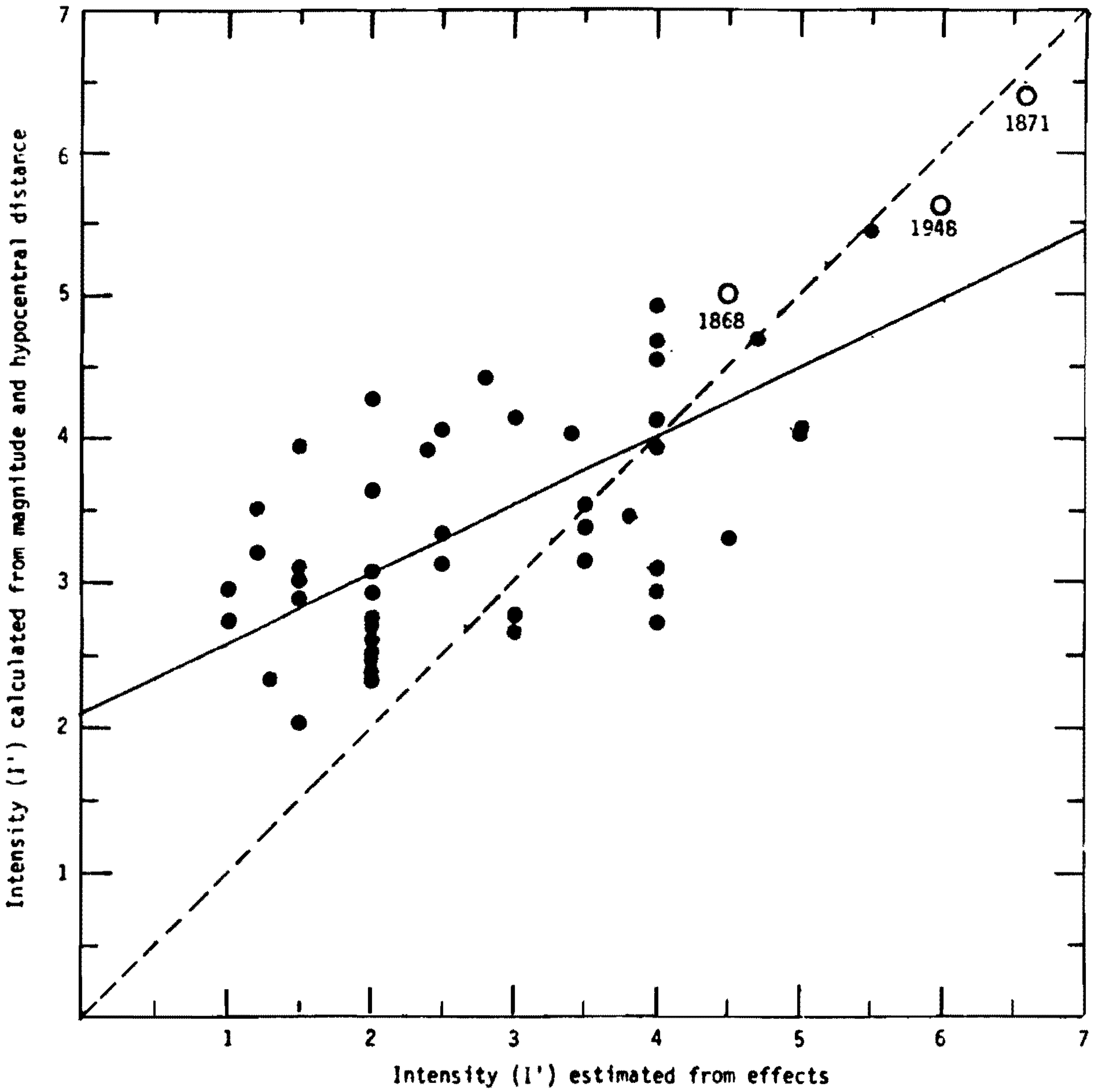

Figure 4. Comparison of estimated Honolulu intensities with values calculated from magnitudes and hypocentral distances.

of their occurrence in the Honolulu newspapers, it could not be assumed that the record was complete with respect to the less newsworthy earthquakes with small intensities, particularly for the period prior to the beginning of seismographic recording in Hawaii.

To test for what intensities the records of various lengths might be reasonably considered complete, cumulative numbers of quakes occurring with various estimated Honolulu intensities were plotted for the entire period. The results suggested: 1) that the 125-year record might be considered essentially complete with respect to earthquakes whose Honolulu intensities were V or greater and inclusive of most quakes whose Honolulu intensities were IV; 2) that the record since about 1910 might be considered essentially complete with respect to quakes of intensity IV or greater; but 3) that even the record for the last few decades could not be safely considered complete with respect to quakes of intensity less than IV.

Test of newspaper-reporting criteria used in intensity estimation

As indicated earlier, notice by the Honolulu newspapers of the occurrence of events and of their Oahu observation was used as one of the criteria for distinguishing between quakes not felt on Oahu and those felt with small intensity; and comment by the newspapers on the effects of the felt quakes was used as one of the criteria for estimating whether or not a quake was felt with significant intensity. Reports other than those in newspapers led to consideration that some quakes reported in newspapers or reported in articles not mentioning Oahu were felt on the island; and, for some of the quakes occurring in the last two decades, there were available estimates of Oahu intensity for quakes whose occurrence, Oahu observation, or Oahu effects were not reported in the newspapers.

To test to what extent the criteria of extent of newspaper reporting of the events might have led, in the case of events whose classification was based on these criteria, to failures to include quakes felt on Oahu, the quakes in the list of those considered felt on Oahu were classified in accordance with: i) whether their occurrences were reported in the newspaper accounts; if so, ii) whether their Oahu observations were noted in the newspaper accounts; and, if so, iii) whether the accounts contained descriptions of their Oahu effects. The results of this classification were compared with the conclusions of the study as to which quakes were actually felt on the island and as to the intensities of those quakes. The comparison indicated that, although the conclusions that some of the quakees were not felt on Oahu might perhaps be erroneous, and although the intensity estimates based on the newspaper accounts might be too low in the case of some of the quakes, it is very unlikely that the reliance on the newspapers accounts led to the disregard of or serious underestimation of any quake whose Honolulu intensity was IV or greater.

Conclusions

In summary, it was concluded from the results of the several tests: 1) that the record of quakes felt on Oahu might be considered complete since 1859 with respect to quakes whose Honolulu intensities (I') were 4.0 or greater, and since about 1910 with respect to those whose Honolulu intensities (I') were 3.5 or greater; and 2) that there was no evidence of significant systematic bias in the estimation in this study of the Oahu intensities of the quakes whose intensities (I') were 3.5 or greater.

FREQUENCY DISTRIBUTION ANALYSIS AND RESULTS

Introduction

Frequencies and return periods

Earthquakes do not occur at regular intervals and hence cannot be said to have regular recurrence frequencies or true periods. It is clear, however, that large earthquakes occur less frequently than small ones, and in what follows the term frequency is used in the sense of average frequency, and return period is used for the inverse of average frequency.

In the presentation of a frequency distrbution of event sizes, the frequency associated with a particular size, s, might take the form of either:

1) F_s = an exceedence frequency, the frequency with which that size is equalled or exceeded; or,

2) $f_s = dF_s/ds$ = a frequency density, the frequency of occurrence of events of that size per unit size range.

The frequencies to which reference will be made most commonly in the report are average exceedence frequencies, F, per year, and the return interval to which reference will be made most commonly are the inverses of those frequencies, $T = 1/F$, in years.

Forms of frequency distribution

It has long been recognized (Gutenberg and Richter, 1949), that earthquakes magnitudes are linearly related to the logarithms of their exceedence frequencies, i.e.:

$$M = a_M - b_M \ln F_M \tag{1a}$$

where M = magnitude

F_M = exceedence frequency of magnitude M

a_M and b_M = regional constants;

and hence that the regional frequency distribution of earthquake magnitudes is of exponential form:

$$F_M = e^{(a_M - b_M M)} \tag{1b}$$

Because the magnitudes of earthquakes are functions of the total energies of the earthquakes, and Modified Mercalli intensities are intended to be functions of energy densities, it is expectable that there should be a fairly regular relationship between the intensities of earthquakes at a place and their average exceedence frequencies. It does not follow that the same relationship between intensity and exceedence frequency must hold over the entire MM scale, because the correlation between MM intensities and such measures of energy density as the maximum accelerations of earthquake motion is far from perfect. It also does not follow that the place-specific frequency distribution of earthquake intensities will necessarily be a simple one if the earthquakes originate in a number of regions in which there are different frequency distributions of quake magnitudes.

The fit of frequency distributions of a number of possible forms to the record of Honolulu earthquake intensities was investigated in this study. As will be shown, very nearly equally good fits were found in the case of distributions of two forms:

1) An exponential form:

$$F = e^{a' - b' I'} \tag{2a}$$

represented in semi-log by plots by the straight lines:

$$\ln F = a' - b' I' \tag{2b}$$

$$\text{or } I' = \alpha' - \beta' \ln F \tag{2c}$$

where I' = intensity in the continuous scale

F = exceedence frequency of I'

a', b', and β' = place-specific constants

$\alpha' = a'/b'$

$\beta' = 1/b'$

2) A power-law form:

$$F = d^{a'} I'^{-b''} \tag{3a}$$

represented in log-log plots by the straight lines:

$$\ln F = a'' - b'' \ln I' \tag{3b}$$

$$\text{or } \ln I' = \alpha'' - \beta'' \ln F \tag{3c}$$

where a'', b'', α'', β'' = place-specific constants

$\alpha'' = a''/b''$

$\beta'' = 1/b''$

A theoretical basis for expecting that at least one of these two forms would fit the record of earthquake intensities experienced at a place, at least if all of the earthquakes originated in a single region, was subsequently found (Cox, 1 6c) through combination of the forms of the following relationships:

a) that between earthquake magnitudes and their recurrence frequencies;

b) that between the total energies of the earthquakes and their magnitudes;

c) that among the the energy density of an earthquake at a place, the distance of that place from the earthquake hypocenter, and total energy of the earthquake;

d) two alternative possible relationships between intensity and energy density.

Frequency distributions of average Honolulu intensities

Estimated distributions

The average Honolulu intensities in the record initially analyzed were those considered most probable, disregarding at first the ranges of uncertainty indicated in Table 1. Because the record of estimated average intensities for Honolulu was much more complete than that for other places on Oahu, only the Honolulu record was subjected to full-scale frequency analysis.

The exceedence frequency of the m'th largest event in each record was computed as $F_m = m/T_r$ where T_r = period of record, as appropriate considering the centering of interest in the frequencies of the larger events.

The record for the period from 1910 through 1983 (T_r = 74 years) was initially considered in addition to and separate from that for the entire period from 1859 through 1983 (T_r = 125 years) because it was expected that, although even the post-1910 part of the record was incomplete with respect to quakes of small intensity, the incompleteness probably extended to higher intensities in the case of the pre-1910 part of the record. For each record analyzed, the quakes were listed in order of intensity.

The intensities and associated recurrence frequencies are shown in the semi-log plot of Figure 5 and the log-log plot of Figure 6.

It will be noted that both records in both plots show much more rapid rates of decrease of intensity with increased frequency for the lower intensities than for the higher intensities, consistent with the assumption that none of the records is complete for the quakes of low intensity.

For intensities of intensity V or greater (I' 4.5) the exceedence frequencies suggested by the two records are in close agreement. However, even for intensities of the upper part of the range of intensity IV (4.0 I' 4.5), the frequencies suggested by the 125-year record are significantly lower than those suggested by the 74-year record. Hence, it was considered that, although the 74-year record could be considered essentially complete with respect to intensities of IV or greater (I' 3.5), the 125-year record could be considered complete only for intensities of V or greater (I' 4.5).

Initially, distributions of exceedence frequencies were fit by least-quakes regression, assuming each of the alternate distribution forms, to the data in each record for the intensities above the cutoff value appropriate to that record. Because the differences between the results could not be considered significant, the final fit of distributions of the two forms was to a composite record consisting of:

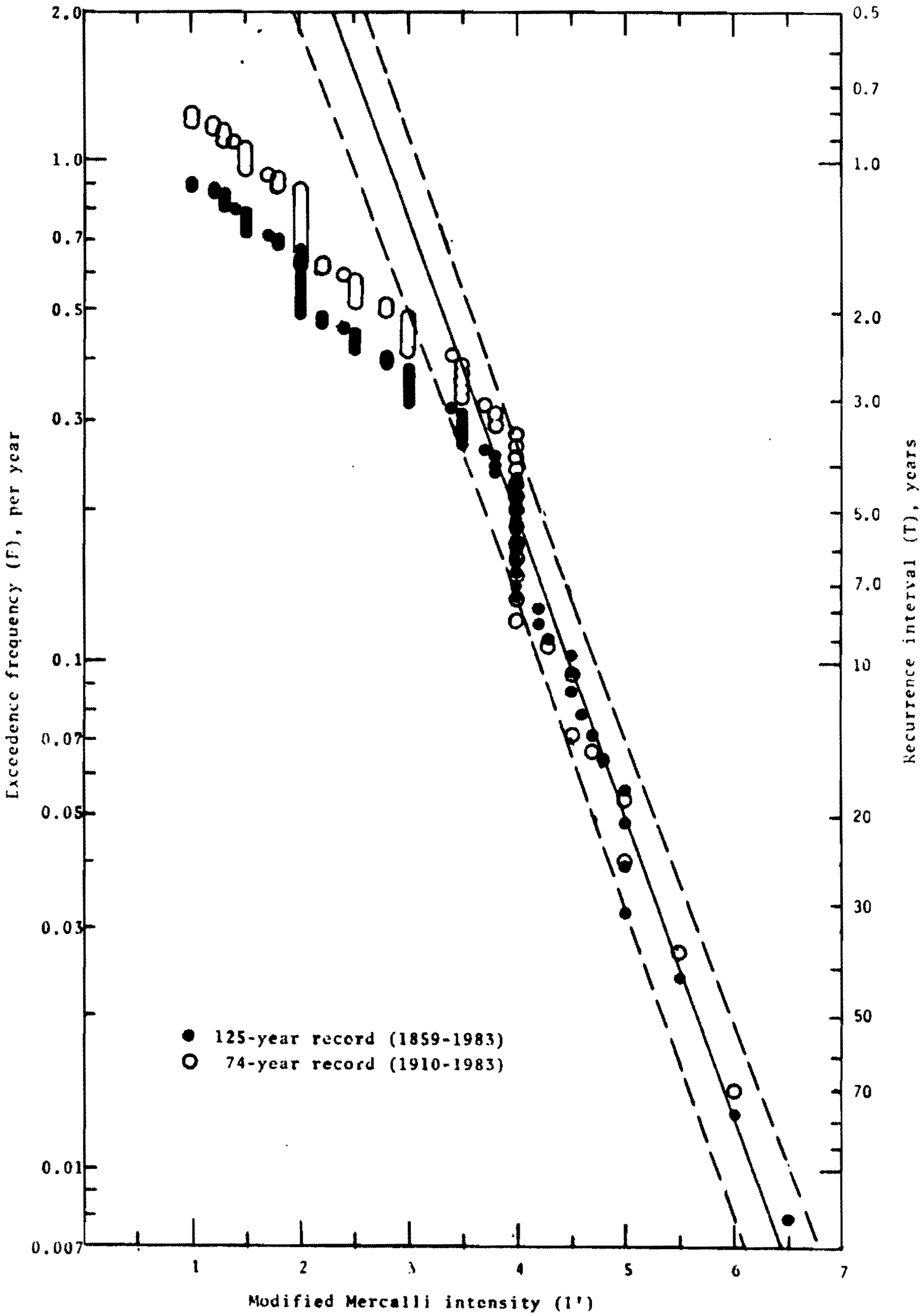

Figure 5. Frequency distribution of Honolulu earthquake intensities assuming distribution of exponential form.

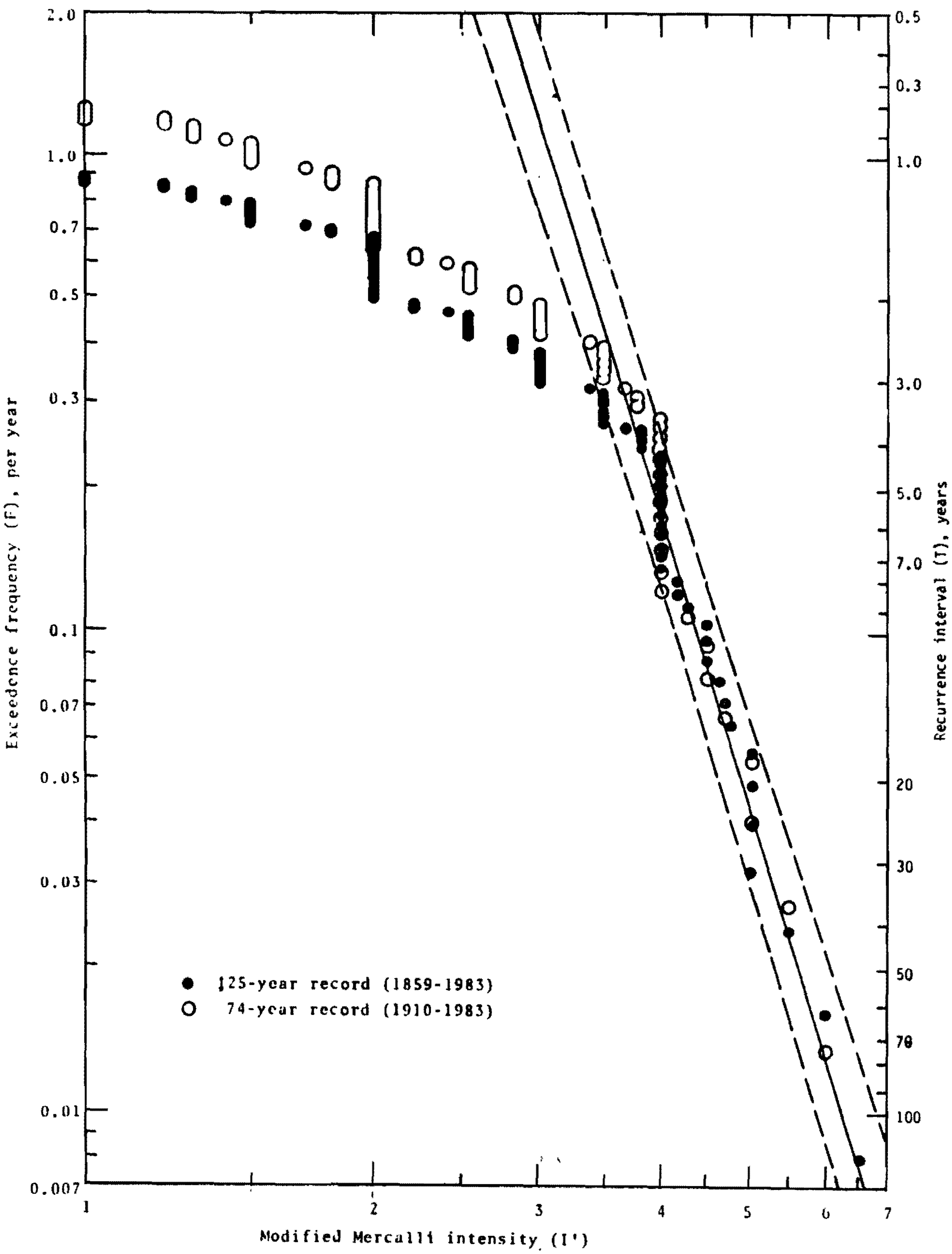

Figure 6. Frequency distribution of Honolulu earthquake intensities assuming distribution of power-law form.

a) The record of the period from 1910 through 1983 (T_r = 74 years) for I' 3.5 and

b) The single quake whose intensity exceeded the maximum experienced from 1910 through 1983, that of February 1871 (I' = 6.5, T_r = 125 years).

For the distribution of either form two regression lines could be fitted by the least-squares method:

i) the line of regression of ln F on I' (or ln I'), with the slope b' and intercept a' of equation (2b) (or slope b" and intercept a" of equation (3b)), which would provide the best estimates of ln F for given values of I' and ln I'; and

ii) the line of regression of I' (or ln I') on ln F, with the slope β' and intercept α' of equation (2c) (or slope α'' and intercept β'' of equation (3c)), which would provide the best estimates of I' and ln I' for given values of F or ln F.

Both regression lines were fitted to the composite distribution, and in addition, limits of prediction for 95 percent confidence were computed corresponding to each of the regression lines for each distribution form.

Furthermore, because interest in the study was not restricted to obtaining the best estimates of the sort represented by the two ordinary regression lines but extended to the best mutual relationship between ln F' and I' (or ln I'), the composite distribution was fitted by mutual regression lines assuming each of the two forms of distribution—lines with slopes lying between b' and $1/\beta'$ (and between b" and $1/\beta''$).

The inputs to the frequency analyses and the results of the analyses are summarized in Table 4. The results include the correlation coefficient (r) for each of the two forms of distribution, and the intercept coefficients, slope coefficients, and standard errors of estimate for each of the regression lines for that form.

To facilitate comparison of the results, values of α and β have been added (in parentheses) to the values of a and b determined directly for the lines of regression of ln F on I' and on ln I'. For these lines, the standard errors are errors in ln F. Similarly values of a and b have been added (in parentheses) to the values of α and β determined directly for the lines of regression of I' and ln I' on ln F. For these lines the standard errors are errors in I' and ln I' respectively. Either the values of a and b or those of α and β may be regarded as directly determinable for the mutual regression lines. For these lines the standard errors are errors measurable normal to the lines.

The solid line added to Figure 5 is the mutual regression line for the composite record assuming a frequency distribution of exponential form. The dashed lines represent limits for 95 percent confidence for the ordinary regression line assuming the same distribution form, each part of each line representating whichever of the prediction limits departs most from the mutual regression line.

Table 4. Input statistics for and results of frequency analysis of composite record of Honolulu intensities.

Input statistics

Period of record, T_r	74 years	125 years
Intensities	$3.5 \leq I' \leq 6.0$	$I' = 6.5$
Number of quakes, n	29	1
Total number of quakes	30	

Results for F expressed per year

Frequency distribution of exponential form
r=-0.980

Regression:	ln F on I'	I' on ln F	Mutual
a'	3.70	(3.93)	3.85
α'	(2.78)	2.83	2.81
b'	1.33	(1.39)	1.37
β'	(0.75)	0.72	0.73
$S_{e(\ln F)}$	0.20	$S_{e(I')}$ 0.15	S_m = 0.01

Frequency distribution of power-law form
r=-0.979

Regression:	ln F on ln I'	ln I' on ln f	Mutual
a''	6.97	(7.38)	7.35
α''	(1.12)	1.13	(1.12)
b''	6.23	0.153	6.51
β''	(0.161)		0.154
$S_{e \ln F}$	0.20	$S_{e(\ln I)}$ 0.032	S_m = 0.001

Estimates of recurrence interval (T = 1/F) in years for quakes of $I \geq$ VII ($I' \geq 6.5$)

Frequency distribution form

T	Exponential	Power-law
Minimum	98	74
Probable	158	125
Maximum	253	192

The equivalents assuming a frequency distribution of power-law form have been added to Figure 6.

Effects of ignoring foreshocks and aftershocks

Because the records subjected to the frequency analyses discussed above included aftershocks and foreshocks as well as principal shocks, and it might be considered that the frequency analyses should be applied to records including only the single most intense quake of a swarm, the effects of deleting the foreshocks and aftershocks from the record was investigated.

In the 125-year record since 1859, the two quakes identified as possible foreshocks or aftershocks had average Honolulu intensities equal to or exceeding the minimum value used in the frequency analysis of that record, $I' = 4.5$.

The first was the intensity 4.8 quake of 12 December 1861 that is considered an aftershock of the intensity 5.0 quake occurring a week earlier. The second was the quake of 4 April 1868 that was treated as if an aftershock of the major earthquake occurring two days earlier (although the Honolulu intensity of the possible aftershock seems to have been slightly higher ($I' = 4.6$) than that of the major quake ($I' = 4.5$) and, hence, its epicental distance from Honolulu may have been significantly smaller than that of the major quake).

Because none of the quakes of 1861 or 1868 had Honolulu intensities exceeding the maximum in the 74-year record since 1910, none of them were included in the composite record analyzed, and ignoring any of them would have no effect on the frequency distributions indicated by the record.

In the 74-year record, only one quake identified as a foreshock or aftershock had an average Honolulu intensity equal to or exceeding the cutoff value used in the frequency analysis, in this case $I' = 3.5$. This was the quake of 13 January 1948 that was identified as a possible foreshock of the quake of 28 January of the same year. Deletion of its intensity, $I' = 3.5$, from the composite record would result in very little change in the frequency distribution.

The estimated frequency distributions for records without foreshocks and aftershocks may, therefore, be considered essentially the same as those computed for the records with foreshocks and aftershocks.

Effects of uncertainty in intensity estimation

It will be recalled that the values of the average Honolulu intensities of the earthquakes in the records initially analyzed were the values considered most probable. In the absence of any evidence of systematic bias in their estimation, it would be unrealistic to substitute systematically either the maximum or the minimum values implied by the ranges of uncertainty, indicated in Table 1. However, the analyses were repeated substituting, successively, the maximum and the minimum values for the average values for the quakes of highest intensity (February 1871 and June 1948). The regression lines in all cases fell within the confidence limits shown in Figures 5 and 6. Hence it seems unlikely that the actual frequency distribution falls outside the limits shown in Figure 5 if it is of exponential form or outside the limits shown in Figure 6 if it is of power-law form.

Frequency distributions for other Oahu areas

The records of historic earthquake intensities in areas of Oahu other than Honolulu are too scanty to warrant their direct use in frequency analyses. However, average intensities have been estimated for three or more of the other areas shown in Figure 1 in the case of all three of the quakes whose average Honolulu intensities were estimated at 5.5 or greater and, for one of the four quakes whose average Honolulu intensity was estimated at 5.0.

Average differences and average ratios of the intensities of the quakes in the other areas and their intensities in Honolulu are presented in Table 5. The table also shows values of the intercept coefficients a' and a'' for the mutual regression lines representing the frequency distributions of the exponential and power-law form, respectively, calculated for the several areas assuming consistency of the slope coefficients b' and b''.

The geographic distributions of intercept coefficients computed were smoothed to produce the distributions shown in Figure 7.

For earthquakes with intensities of VII or greater ($I' \geq 6.5$) in the Waialua area on the northwestern coast of Oahu, the smoothed distributions suggest a probably recurrence interval of about 610 years assuming the frequency distribution is of exponential form and about 480 years if the frequency distribution is of power-law form.

Probability implications and limitations of frequency distributions

Probability implications assuming random temporal distribution

If it is assumed that earthquakes are randomly distributed in time, and more specifically that their temporal distribution is a Poisson one, the probability of occurrence of one or more earthquakes of a certain size range during any particular time interval is given by the formula:

$$P = 1 - e^{-t/T} = 1 - e^{-tF}$$

where t = duration of time interval

Occurrence probabilities computed by this formula for earthquakes with average Honolulu intensities of VII or greater (I' 6.5) are plotted as functions of time-interval duration in Figure 8; assuming, alternatively, that the average exceedence frequency of such earthquakes is that indicated by the mutual regression lines of each of the two forms and by the most extreme of the 95-percent prediction-limit lines.

Implications of seismic-gap theory

Although there is no reason to doubt that the temporal distribution of earthquakes is in general random, there is increasing evidence to support what has become known as seismic-gap theory, in accordance with which the occurrence of large earthquakes on a particular part of a particular fault system is roughly periodic. For time intervals much longer than the average recurrence periods,

Table 5. Differences in intensities and in intercept coefficients for frequency distributions of intensities for areas of Oahu.

	Honolulu	Kailua-Waimanalo	Kaneohe	Central	Pearl Harbor	Waianae	Waialua	North Shore
η[1]		3	3	3	4	3	2	1
Δ[2]		-0.07	-0.03	-0.43	-0.50	-0.67	-0.85	-1.00
r[3]		0.99	0.99	0.92	0.91	0.88	0.84	0.80
α'[4]	2.81	2.74	2.77	2.37	2.31	2.14	1.96	1.81
a'[4]	3.85	3.76	3.80	3.25	3.16	2.93	2.58	2.48
α''[5]	1.13	1.12	1.12	1.05	1.04	1.00	0.96	0.91
a''[5]	7.35	7.28	7.32	6.81	6.76	6.50	6.26	5.90

Notes:

1) η: number of earthquakes in average (I')

2) Δ: arith. mean intensity for place - arith. mean intensity for Honolulu

3) r: ratio of geom. mean intensity for place to geom. mean intensity for Honolulu

4) α', a': intercept coefficients, mutual regression line, frequency distribution of exponential form, for F expressed per year

5) α'', a'': intercept coefficients, mutual regression line, frequency distribution of power-law form, for F expressed per year

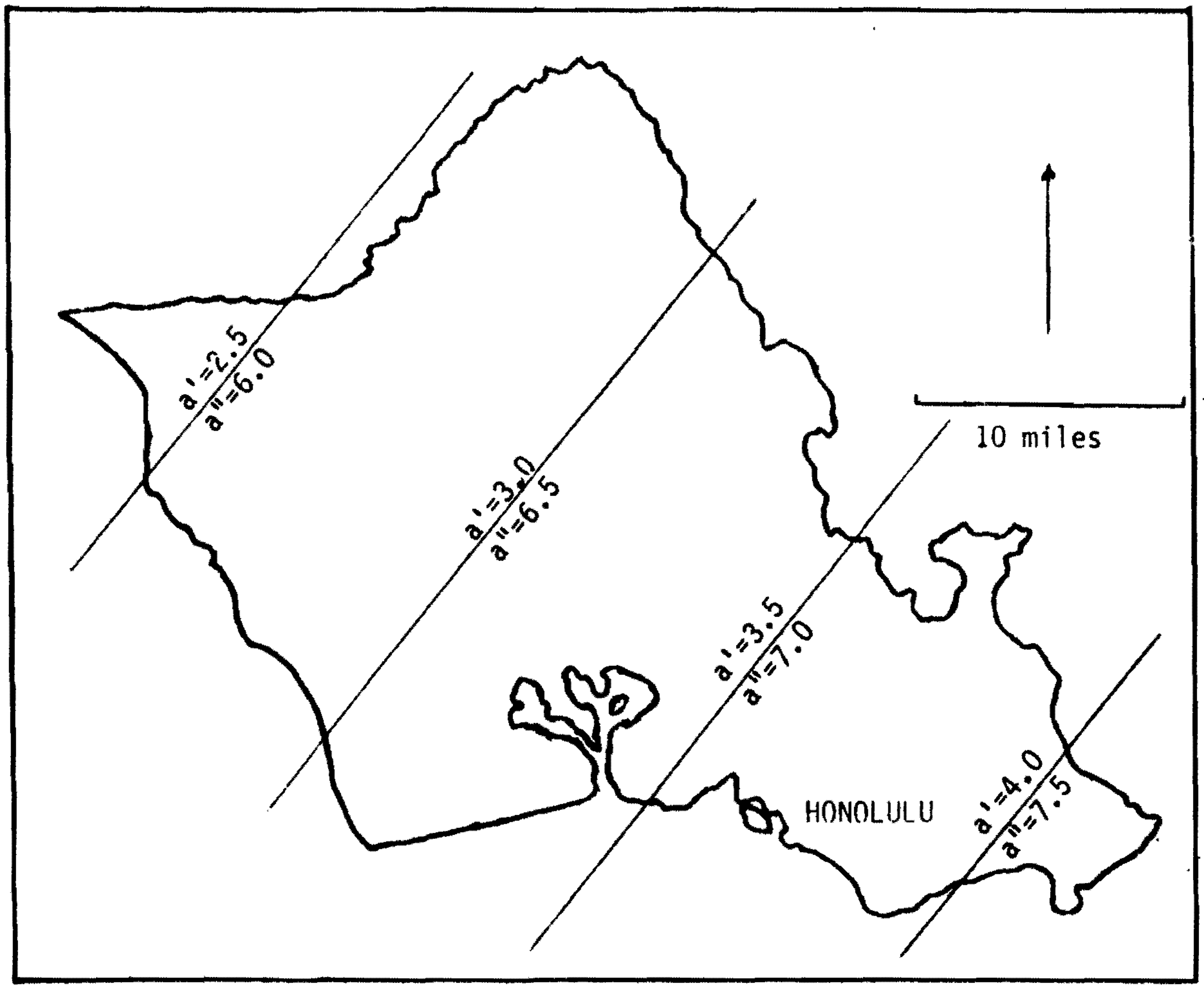

Figure 7. Geographic distribution of intercept coefficients of frequency distributions of intensities.

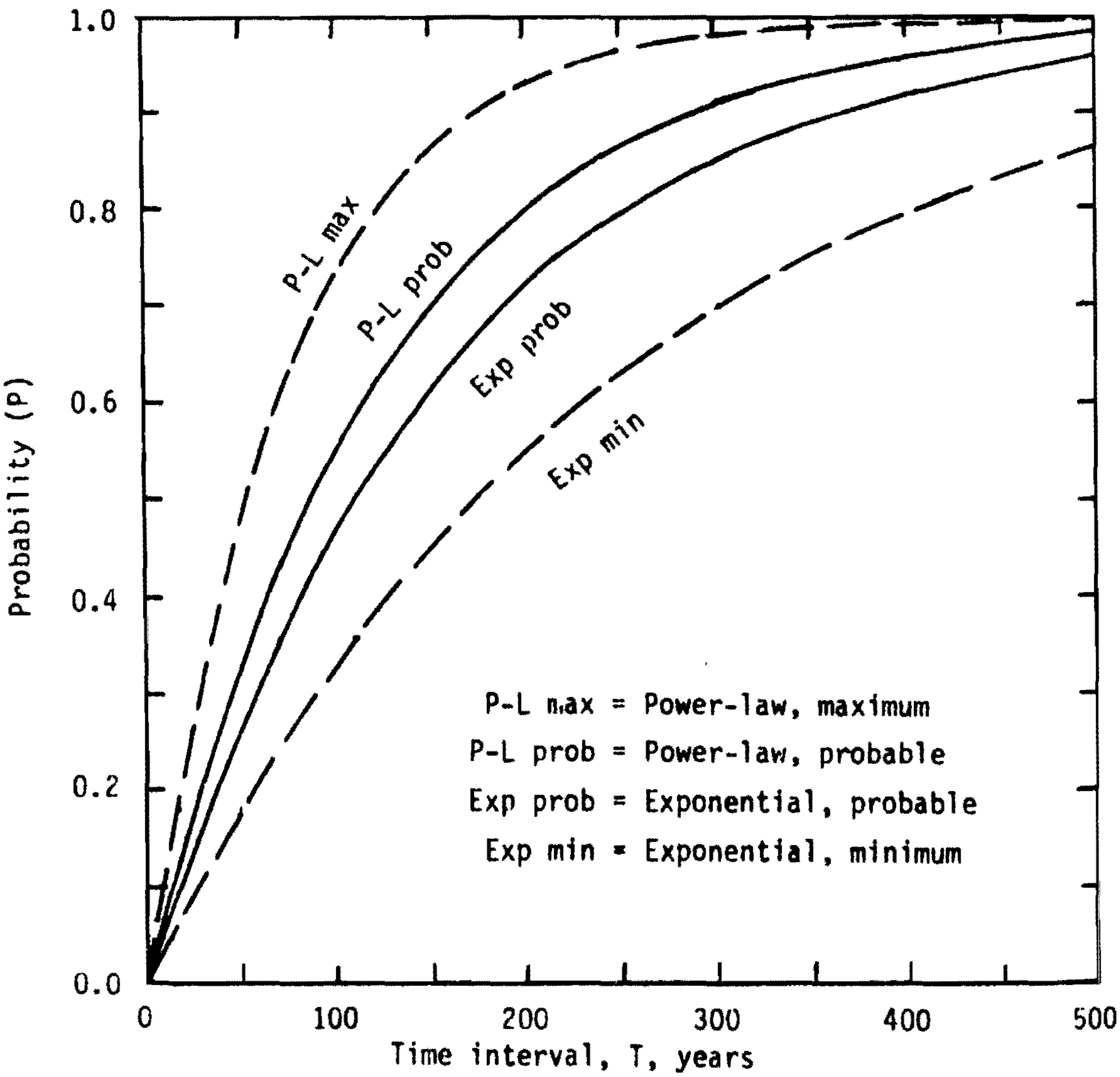

Figure 8. Probabilities of exceedence of intensity I'=6.5 in Honolulu

probabilities of occurrence estimates assuming quasi-periodic temporal distribution would not differ significantly from those assuming random distribution. For shorter time intervals, however, there might be considerable differences between the two sets of probabilities, and, assuming the distribution for the large quakes were approximately periodic, the frequency distribution calculated from a period of record might be steeper or flatter than the long-term frequency distribution depending on whether the period of record included or did not include one of the large quakes.

As indicated in Figure 3, the earthquakes felt on Oahu have not originated on a single fault system, and, even if the generation of large quakes along the several systems on which the felt quakes originated were semi-periodic, it is quite unlikely that the periods and phases for all of the systems are the same. However, the possibility that the existence of a seismic gap on some fault system might significantly affect the slope of the frequency distribution estimated for Honolulu intensities seemed worth investigation.

The fault system that seemed most likely to give rise to a significant effect was the Diamond Head fault whose existence was postulated by Furumoto et al. (1980) and Furumoto (1983) on the basis of the approximate alignment of the epicenters of earthquakes occuring in the period from 1962 through 1981. Cox's finding (in press, a) that the epicenter of the June 1948 Oahu earthquake was probably on the trend of this postulated fault lends some support to its existence. The fact that the 1948 earthquake had the second highest Honolulu intensity in history would lend special significance to a possible seismic gap on it. The possibility of such a gap cannot be disproved. However, as shown by Cox, the frequency distributions of both the magnitudes and the Honolulu intensities whose epicenters lay or might have lain along the postulated fault suggests the absence rather than the presence of a current seismic gap.

SUMMARY

The principal conclusions reached in this study may be summarized as follows:

1. One hundred and thirteen earthquakes are known to have been felt on Oahu in the period from 1859 through 1983.

2. Of these earthquakes, that whose probable average intensity was highest in Honolulu ($I' = 6.5$, on the boundary between MM VI and MM VII), was one that originated in 1871 on or near the south coast of Lanai. That with the second highest probable average Honolulu intensity ($I' = 6.0$, in the middle of the range of MM VI), originated in 1948 just off the south coast of Oahu at Honolulu. Eleven more quakes had intensities of V or greater ($4.5 \geq I' \geq 5.5$).

3. The frequency distribution of the average Honolulu intensities of the quakes whose intensities was III or greater may be described well by either an exponential distribution function or a power-law one. The functions are:

   Exponential form: $F = e^{3.70 - 1.33\, I'}$

   Power-law form: $F = e^{6.97}\, I'^{-6.23}$

4. The return interval for earthquakes with intensities of VII or greater ($I' \geq 6.5$) in Honolulu lies with 95 percent confidence between 74 and 253 years and probably between the value of 125 years suggested by the distribution of power-law form and the value of 158 years suggested by the distribution of exponential form.

5. The recurrence interval for earthquakes of intensities of VII or greater ($I' \geq 6.5$) on the northwest coast of Oahu lies probably between about 480 and 610 years.

REFERENCES

Bert, E., E. Botsai, A. Chiu, D.C. Cox, and F. Duennebier, in prep. Seismic risk zoning for Oahu, Hawaii.

Cox, D.C., 1985a. The Lanai earthquake of February 1871. Univ. Hawaii Env. Ctr. Spec. Rpt. SR:0034, 50 pp.

Cox, D.C., 1985b. Approximate relationship of intensity to magnitude and hypocentral distance for Hawaiian earthquakes. Univ. Hawaii Env. Ctr. Spec. Rpt. SR:0035, 23 pp.

Cox, D.C., 1986a. The Oahu earthquake of June 1948, associated shocks, and the hypothetical Diamond Head fault. Univ. Hawaii Env. Ctr. Spec. Rpt. SR:0036, 32 pp.

Cox, D.C., 1986b. Earthquakes felt on Oahu, Hawaii, and their intensities. Univ. Hawaii Env. Ctr. Spec. Rpt. SR:0038, 120 pp.

Cox, D.C., 1986c. Frequency distributions of earthquake intensities and the distribution at Honolulu. Univ. Hawaii Env. Ctr. Spec. Rpt. SR:0041, 21 pp.

Furumoto, A.S., 1983. Recent data for seismicity of Hawaii in regards to seismic zoning, Appendix B (11 pp.) in Emergency Preparedness and Response, Citizen's Blue Ribbon Committee report to City Council, City and County of Honolulu.

Furumoto, A.S., W. Lum, N.N. Nielsen, and J.T. Yamamoto, 1980. A Study of Earthquakes Losses in the Honolulu Area: Data and Analysis. Rpt. to Hawaii State Civil Defense Div.

Howell, B.F. and T.R. Schultz, 1975. Attenuation of Modified Mercalli intensity with distance from the epicenter. Bull. Seismol. Soc. Amer., vol. 65, no. 1, pp. 651-665.

International Conference of Building Officials, 1979. Earthquake regulations, sec. 2312 in Uniform Building Code, vol. I, pp. 126-147.

Wood, H.O., and F. Neumann, 1931. Modified Mercalli Scale. Bull. Seismol. Soc. Amer., vol. 21, no. 4, pp. 227-281.

APPENDIX: COMPARISON OF PREVIOUS ESTIMATES OF 475-YEAR EARTHQUAKE INTENSITY AT HONOLULU WITH ESTIMATES BASED ON THIS STUDY

The estimates

The results of what may be considered a set of previous indirect estimates of frequency distributions of earthquake intensities in Hawaii have come to attention in the form of a map of MM intensities for a return period of 475 years, published by Petak and Atkisen (1982) and attributed by them to Wiggins (1975). The map shows two values for each isointensity zone, the lower being, according to J. H. Wiggins (personal communication), the intensity expectable at "normal soil" sites and the higher that expectable at "soft soil" sites. Honolulu is shown on the map in a zone identified with a "normal soil" intensity of VII and a "soft soil" intensity of VI. By interpolation from the position of Honolulu relative to the boundaries of the zone, the corresponding continuous-scale equivalents (I') would be about 6.8 and 5.8 respectively.

The Wiggins values are compared in Table A-1 with values estimated from the frequency distributions of both exponential and power-law form derived in this study taking F = 1/T = 1/475 years = 0.00211 per year. The average intensities of the historic earthquakes estimated in this study are, presumably, less than those experienced at "soft soil" sites; and an average expectable intensity estimate based on the historic record should probably be considered to pertain to "normal soil" sites. It will be noted, however, that even the "soft soil" value estimated by Wiggins for Honolulu is less than the minimum (95% confidence) interval values in this study. The "normal soil" value estimated by Wiggins is 1.5 to 2.2 intensity units less than the average values indicated by the mutual regression lines estimated in the study assuming the two forms of frequency distribution.

Previous methodology

According to J.H. Wiggins (personal communications), the expectable intensities were estimated from the results of analyses reported in the National Bureau of Standards Building Series (Culver *et al.*, 1975). In the following outline of the reported methods of analysis, notation in conformity with that used elsewhere in this report is substituted for the original notation.

In Culver *et al.*, it was the magnitudes of earthquakes rather than the intensities to which frequency analysis was applied directly, it being recognized that in any region, approximately:

$$\log F = S - BM \qquad (1)$$

where M = Richter magnitude

F = exceedence frequency of M

B and S = constants

Table A-1. Comparison of MM intensities at Honolulu estimated by Wiggins for 475-year return interval with those estimated in this study.

Values estimated by Wiggins (1975) (Petak and Atkissen, 1982)

Normal soil sites		Soft-soil sites	
I	I'	I	I'
VI	(5.8)*	VII	(6.8)*

*Values of I' in parentheses are estimated from position of Honolulu relative to boundaries of iso-intensity zones mapped by Wiggins.

Values estimated in this study

Minimum (95% confidence)		Mutual regression: Exponential form		Mutual regression: Power-law form		Maximum 95% confidence	
I'	I	I'	I	I'	I	I'	I
6.9	VII	7.3	VII	8.0	VIII	8.8	IX

It was assumed that only the intercept coefficient, S, is a site-specific or region-specific constant, referred to as "seismicity," whereas B is a universal constant with the value of 0.9.

Two earthquake records were used in the analysis:

1) A "NOAA" record for the 12-year period 1961 through 1973, compiled from the NOAA bi-monthly publication World Earthquakes, assumed to be complete with respect to quakes of magnitude 3.5 or greater;

2) A "historic" record for earthquakes occurring before 1961, compiled from Eppley (1965), from which were taken the MM intensities and felt areas of the quakes rather than the magnitudes. The record was assumed complete with respect to quakes with epicentral intensities of IX or greater, but incomplete with respect to smaller quakes. The earliest Hawaiian quake in the record occurred in 1834; and it was assumed that only half of the Hawaiian quakes with epicentral intensities of VII and VIII and only a quarter of those with epicentral intensities of V and VI were included in the record.

In the case of a quake with a reported epicentral intensity reported in the "historic record," the magnitude was estimated from:

$$I_o = 1.5\,(M-1) \tag{2}$$

where I_o = epicentral intensity

In the case of the quake with a reported felt area, use was made of the intensity attenuation relationship:

$$I = k_1 + 1.5\,M - k_2 \log \Delta \tag{3}$$

where I = MM intensity

Δ = epicentral distance

k_1 and k_2 = regional constants, considered identical in Hawaii to those of the western states of the continental U.S.

Equation (3) was applied considering that, at the boundary of the felt area the intensity was $I_f = 4$ and the epicentral distance was $\Delta_f = \sqrt{A_f/\pi}$, where A_f = area within which the quake was reported felt.

Equation (1) was used to derive "seismicities" from each of the earthquake records using the data on earthquakes of M 3.5 grouped by both magnitude and epicentral location. For the epicentral location grouping, a region was subdivided into cells whose boundaries were meridians and parallels of half-degrees of longtitude and latitude respectively. For the magnitude grouping the quakes were placed in groups differing by half a magnitude unit. "Seismicities" were computed for both individual cells and for multiple-cell "search areas." The "search area" for any region was defined as that within which the largest earthquake of record for the region, $M = M_{r\,max}$, might have caused damage, its radius, Δ_a, being calculated from equation (3) taking the intensity as $I_a = 6.7$, the intensity assumed necessary to cause significant damage.

In the case of either an individual cell or a "search area," the "seismicity" was calculated as the average of the "seismicities" indicated using equation (1) by the several magnitude groups pertinent to the cell or area; and in the case of the "search areas", at least, standard deviations also were computed. The formulas used were:

$$S = \frac{1}{m} \sum_{i=1}^{m} S_i \tag{4a}$$

$$S_a = \frac{1}{m} \sum_{i=1}^{m_a} S_i \tag{4b}$$

$$\sigma_a = \sqrt{\frac{1}{m} \sum_{i=1}^{m} (S_i - S_a)^2} \tag{5}$$

where m = number of magnitude groups for cell

m_a = number of magnitude groups for "search area"

S = seismicity of cell

S_a = seismicity of "search area"

$S_i = BM_i + \log F_i$ = seismicity indicated by magnitude group i

F_i = exceedence frequency for group i

M_i = magnitude for group i

It should be noted that F_i was calculated as N_i/T_i where N_i was taken as the number of quakes of record whose magnitudes equalled or exceeded the maximum magnitude in group i, whereas M_i was taken to be the central magnitude of group i.

A maximum expectable magnitude, M^*_{ea}, associated with a particular return period, T^*, for earthquakes whose epicenters lay within a particular search area could be estimated from equation (1) in the form:

$$M^*_{ea} = S_{ea} - \log F^*_a \tag{6}$$

where $F^*_a = 1/T^*$

$S_{ea} = S_a + n_e \sigma_a$ = "engineering seismicity" for area a

n_e = factor depending on the desired confidence level

($n_e = 0$ for 50% confidence,

$n_e = 2$ for 95% confidence)

The maximum expected magnitude, calculated taking n = 0, was defined as a "representative magnitude" for return period T*:

$$M^* = S_a + \log T^* \tag{7}$$

In addition to the values of S_a and σ_a, a value of a "representative expectable distance", Δ^*_a was calculated for each "search area." In the calculation it was assumed that:

$$V = C_1 \, 10^{C_2 M_\Delta - C_3} \tag{8}$$

where V = bedrock particle velocity at hypocentral distance Δ,

$$\text{and that } V_a^{*\,B/C_2} = \sum_{j=1}^{n} V_j^{B/C_2} \tag{9}$$

where V_a^* = velocity in the central cell of the "search area" resulting from an earthquake of magnitude M* at epicentral distance Δ^*

V_j = velocity in the central cell of the "search area" resulting from an earthquake with an epicenter in cell j of the "search area" having a magnitude with an exceedence frequency in that cell equal to F*

n_a = number of cells in the search area

By the combination of equations: (7) - (9):

$$\Delta^* = \left(\sum_{j=1}^{n} 10^{Si-Sa} \Delta_i^{-BC_3/C_2)} \right)^{-C_2/BC_3} \tag{10}$$

Application of previous methodology to Honolulu

The values of the regional constants considered pertinent to Hawaii were:

$C_1 = 0.0237$	$k_1 = 2.786$
$C_2 = 5.63$	$k_2 = 3.742$
$C_3 = 0.0395$	$\Delta_a = 145$ miles

For the cell in which Honolulu is located, the values of the "search area" seismicity and its standard deviation and of the "representative epicentral distance" as estimated from the two records were:

	Historic record"	"NOAA record"
S_a	4.260	3.137
σ_a	0.300	0.187
Δ_a	133.14	145.74

By the combination of equations (3) and (8), the maximum intensity expectable from an earthquake of "representative magnitude" at the "representative epicentral distance" would be:

$$I^* = k_1 + 1.5\,(S_a + \log T^*) - k_2 \log \Delta^* \qquad (13)$$

For a return interval $T^* = 475$ years, the maximum Honolulu intensities indicated by substituting in equation (13) the values obtained from the two records are:

$$I^* = 6.4 \text{ (from "historic record")}$$

$$I^* = 5.7 \text{ (from "NOAA record")}$$

According to Culver et al., use was made of the higher of the values indicated by the two records. Translating the higher of the decimal values of I given above to the corresponding values on the continuous intensity scale used in this report ($I' = I^* - 0.5$), $I' = 5.9$, differing only 0.1 intensity unit from the "normal soil" value estimated from the position of Honolulu relative to the boundaries of the isointensity zones mapped by Wiggins (Table A-1).

Critique

Even if the frequency analysis had been applied to a synthetic record of Honolulu intensities estimated from the magnitudes or epicentral intensities of historic earthquakes, the results would be less reliable than those of applying the analysis to the record of Honolulu intensities estimated directly from the Honolulu effects of the earthquakes. Increased unreliability must attach to the indirect estimation of the maximum Honolulu intensity for a particular return interval as that resulting from an estimated "representative magnitude" at a "representative epicentral distance." There are, in addition, two sources of underestimation in the estimates based on Culver et al.

As noted earlier, M_i was taken to be the central magnitude of the quakes of magnitude group i. The magnitude to which the exceedence frequency S_i should have been considered associated is the maximum magnitude of the group i quakes, 0.25 magnitude units greater than the value taken. Actual values of S_a and of M_a should therefore be 0.25 units greater than those estimated, and the estimated values of I* should be increased by (1.5 x 0.25)/0.9 = 0.4 intensity units.

A more serious source of underestimation results from the probability that the magnitudes of the two earthquakes that had the highest Honolulu intensities in history were greatly underestimated by applying the Culver et al. methods to the record of quakes in the Earthquake History of the United States (Eppley, 1973).

The earthquake whose intensity in Honolulu is considered in this study to have been the highest in history is that of February 1871 (I' = 6.5 ± 0.7; I = VI or VII). For this earthquake even the most recent edition of the Earthquake History (Coffman et al., 1982) lists neither a felt area nor an epicentral intensity. Although the magnitude of the earthquake (estimated in this study at 7.0 ± 0.5) was probably among the three greatest magnitudes in Hawaiian history, the quake was included in a list of "Intermediate and minor earthquakes", and its Oahu effects were noted simply as "Felt strongly at Honolulu."

The earthquake whose Honolulu intensity is considered in this study to have been the second highest in history was that of June 1948. An epicentral intensity of V is listed in Coffman et al., (1982) for this earthquake, although its intensity at Honolulu is estimated in this study to have been VI (I' = 6.0 ± 0.7).

Conclusions

A 12-year period such as that of the NOAA (1961-1972) record is much too short to provide reliable long-term earthquake statistics. The 127-year length of the "historic" record (1834-1961) would be satisfactory. However, the indirect method of analysis applied to this record to obtain the Wiggins estimates of 475-year quake intensity at Honolulu seems much less satisfactory than a determination of the frequency determination of intensities estimated directly from the effects of historic quakes, such as used in the current study, even if the 127-year record were complete and accurate. In the light of the record's underestimation of the two historic quakes with highest Honolulu intensities, it appears that the expectable Honolulu intensities estimated by Wiggins are much less reliable than those estimated in this study.

References

Culver, C.G., G.C. Hart, and C.W. Pinkham, 1975. Natural Hazards Evaluation of Existing Buildings, Natnl. Bur. Stds. Building Science Series 61.

Coffman, J.L., C.A. von Hoke, and C.W. Storer, eds., 1982. Earthquake History of the United States, Natnl. Ocean. Atmospher. Admin., and U.S. Geol. Survey, Publ. 41-1, 208 pp. with suppl. 50 pp.

Eppley, R.A. (ed), 1965. Earthquake History of the United States, U.S. Coast and Geodetic Survey, no. 41-1, Part I, 1965, Part II, 1966.

Petak, W.J. and A.A. Atkissen, 1982. Natural Hazard Risk Assessment and Public Policy. Springer-Verlag, N.Y., 498 pp.

Wiggins, J.H. 1975. Seismic hazard maps of the United States, prepared for Massachusetts Institute of Technology. J.H. Wiggins Co., Redondo Beach, Calif. (Cited by Petak and Atkissen, 1982).