LIQUEFACTION HISTORY, 416-1997, IN JAPAN

Kazue WAKAMATSU[1]

SUMMARY

Liquefaction has been known to occur repeatedly at the same site during successive earthquakes. Maps showing locations of past liquefaction occurrences are very useful to delineate and characterize areas of liquefaction susceptibility for future earthquakes. In this study, historical occurrences of liquefaction during the period of 416-1997 in Japan are investigated through documentary study, post-earthquake reconnaissance surveys, and interviews to local residents. A total of 140 earthquakes which induced liquefaction are listed and a map showing distribution of liquefied sites in these earthquakes is compiled. Plains and/or basin where liquefaction occurred repeatedly during successive earthquakes are presented. Seismic intensities, which induced liquefaction effects, are examined and relationships between the distance from epicenter to the farthest liquefied sites and an earthquake magnitude are studied based on the liquefaction data from the earthquakes.

INTRODUCTION

Liquefaction is known to occur repeatedly at the same site during more than one earthquake as shown by examples from Japan and United States [Kuribayashi and Tatsuoka, 1975; Youd, 1984; Yasuda and Tohno, 1988, Wakamatsu, 1991]. Thus, maps showing the locations of past liquefaction may be considered as potential areas of liquefaction in future earthquakes. The author has compiled records on occurrences of liquefaction during 123 Japanese earthquakes during the period of 416-1990 into a book entitled "Maps for historic liquefaction sites in Japan" [Wakamatsu, 1991]. Since 1990, extensive liquefaction has been induced during several earthquakes including the 1995 Hyogoken Nanbu earthquake. In addition, new data have been found concerning the historical earthquakes. This paper supplements the previous work by the author with new data from the earthquakes after 1990 as well as historic earthquakes, and discussed some characteristics of liquefaction occurrences in Japan.

EARTHQUAKE INVESTIGATED

Up to the present, approximate 850 destructive earthquakes have been recorded in various kind of historical materials and seismic data in Japan [Usami, 1996]. The oldest one among the earthquakes is the August 23, 416 earthquake, which was documented in the "Nihon Shoki", authorized historical document of Japan. These 850 earthquakes during the period of 416-1997 in Japan were investigated in this study. They include about 450 earthquakes until 1884, which documented in nonscientific materials and about 400 recent earthquakes after 1884 when a nationwide earthquake observation was started in Japan. No instances of prehistoric liquefaction, which were revealed by excavation, are included in the liquefaction sites in this study, for date of the earthquake which induced liquefaction can be hardly identified.

[1] *Institute of Industrial Science, University of Tokyo, Tokyo, Japan E-mail: Wakamatu@iis.u-tokyo.ac.jp*

IDENTIFICATION OF LIQUEFACTION OCCURRENCES

To search for records of liquefaction effects, various kinds of materials on earthquake damage were collected. They include several compilations of historic materials on the earthquakes prior to 1884. In addition, in several earthquakes the author performed post-earthquake reconnaissance investigations and interviews to local residents. In the investigations, occurrences of liquefaction were identified by observed sand and water boiling and/or floating up of buried structures, but observed fissures, flowslides, ground subsidence and settlement of structures without sand and/or water boils were excluded from signs of liquefaction effect.

EARTHQUAKES WHICH CAUSED LIQUEFACTION

The investigation revealed that totally 140 events induced liquefaction at several thousand sites during the period of 416-1997 including the original 123 earthquakes previously presented by the author. These 140 earthquakes are summarized in Table 1. The magnitude of earthquakes induced liquefaction ranges 5.2 to 8.4. The oldest event which was identified to induce liquefaction is the 745 earthquake occurred in Gifu Prefecture located central part of Honsyu Island, whereas the latest one is the 1997 Kagoshimaken Hokuseibu earthquake which attacked Kusyu Island (After then, liquefaction occurred at Yuza, Yamagata Pref. during February 26, 1999 earthquake). Since 1884 from which systematic earthquake observation has been carried out in Japan, 77 earthquakes have generated liquefaction. Thus liquefaction has occurred twice in every three years at somewhere in Japan during the last 113 years.

LOCATION OF HISTORIC OCCURRENCES OF LIQUEFACTION

Figure 1 plots liquefied sites due to the earthquakes after 1884, in which locations of liquefaction could be identified. Excepting a few cases, the liquefied sites located on low-lying areas whose subsurface ground is consist of Holocene alluvial fan, fluvial, deltaic, beach and aeolian deposits and artificial fills. In some areas such as the plains of Nohbi, Akita, Niigata, Kanto, Osaka, Kanazawa, Tsugaru, Tokachi, Sendai, Takada, Shizuoka and Tenryu, and Kyoto Basin, liquefaction observed in more than five successive earthquakes for the last fifteen centuries.

The sites of liquefaction extend over the area of several hundreds kilometers in diameter due to the large earthquakes with the magnitude of the order of eight or more such as the Oct.28, 1891 (Nohbi) and the Dec.21, 1946 (Nankai) earthquakes in Figure 1. In contrast, the liquefaction effects developed within the source area during the small earthquakes with the magnitude less than six such as the earthquakes of July 22 1887, Jan. 3 1892, Sep.7 1893, Jan.17, 1897, July 4, 1925, Oct.27 1927, Oct.17 1930, Oct.19 1955, and Feb. 27 1961 in Figure 1.

SEISMIC INTENSITY AT LIQUEFIED SITE

Extent of liquefaction susceptible area can be easily estimated in an earthquake based on seismic intensity if a correlation is established between past liquefaction occurrences and seismic intensity. Figure 2 shows distributions of liquefied sites and seismic intensities on the Japan Meteorological Agency (J.M.A.) scale in the recent earthquakes. The most of the liquefied sites in each earthquake located within the zones of intensity V and greater (The different seismic intensity scales including J.M.A. and M.M. are correlated in Figure 3).

Figure 4 shows seismic intensity at liquefied sites on the J.M.A. sale in the earthquakes after 1964. The graph also indicates that the liquefaction is generally induced by seismic shaking with intensity V and greater on the J.M.A. scale as previously pointed out in Figure 2. However, minor cases of liquefaction occurred at less than V. Figure 5 shows geomorphological conditions at the sites where liquefaction occurred at less than V shown in Figure 4. Most of the sites are on the conditions which have been considered as the most susceptible to liquefaction such as reclaimed land and former river channel, although J.M.A. scale at the times of the earthquakes is based on intensities over relatively large area which may not fully take account of local site conditions.

Table 1: Earthquakes which Induced Liquefaction during the Period of 416-1997

No.	Date	Epicenter [Usami, 1996]	Focal depth (km)	Magnitude [Usami, 1996]
1	745	35.4°N, 135.5°E	unknown	7.9
2	850	39.0°N, 139.7°E,	unknown	7.0
3	July 10, 863	unknown	unknown	unknown
4	August 13, 1185	35.0°N, 135.8°E	unknown	7.4
5	Oct. 9, 1257	35.2°N, 139.5°E	unknown	7.0 - 7.5
6	May 13,1449	35.0°N, 135.75°E	unknown	5¾ - 6.5
7	July 9, 1498	33.0°N, 132.¼°E	unknown	7.0 - 7.5
8	May 12, 1510	unknown	unknown	unknown
9	Jan. 18, 1586	36.0°N, 136.9°E	unknown	7.8 ± 0.1
10	Sep.5, 1596	34.65°N, 135.6°E	unknown	7.½ ± ¼
11	Sep.5, 1596	34.65°N, 135.6°E	unknown	7½ ±¼
12	Feb. 3, 1605	33.5°N, 138.5°E	unknown	7.9
13	March 1, 1633	35.2°N, 139.2°E	unknown	7.0 ± ¼
14	Oct. 18, 1644	39.4°N, 140.0°E	unknown	6.5 ± ¼
15	June 16, 1662	35.2°N, 135.95°E	unknown	7¼ - 7.6
16	Feb. 1, 1666	37.1°N, 138.2°E	unknown	6¾
17	Oct. 7, 1685	unknown	unknown	unknown
18	June 19, 1694	40.2°N, 140.1°E	unknown	7.0
19	Dec. 12, 1694	unknown	unknown	unknown
20	Dec. 31, 1703	34.7°N, 139.8°E	unknown	7.9 - 8.2
21	May 27, 1704	40.4°N, 140.0°E	unknown	7.0 ± ¼
22	Oct. 28, 1707	33.2°N, 135.9°E	unknown	8.4
23	May 13, 1717	38.5°N, 142.5°E	unknown	7.5
24	1717	36.½°N, 136.½°E	unknown	6¼
25	Dec. 19, 1723	32.9°N, 130.6°E	unknown	6.5 ±¼
26	Nov. 29, 1724	unknown	unknown	unknown
27	March 8, 1729	unknown	unknown	unknown
28	1734	unknown	unknown	unknown
29	Jan. 3, 1738	37.0°N, 138.7°E	unknown	5½
30	March 26, 1751	35.0°N, 135.8°E	unknown	5.5 - 6.0
31	May 21, 1751	37.1°N, 138.2°E	unknown	7.0 - 7.4
32	Oct. 31, 1762	38.1°N, 138.7°E	unknown	7.0
33	March 8, 1766	40.7°N, 140.5°E	unknown	7¼ ± ¼
34	Aug. 29, 1769	33.0°N, 132.1°E	unknown	7¾ ± ¼
35	June 11, 1774	Unknown	unknown	unknown
36	August 23, 1782	35.4°N, 139.1°E	unknown	7.0
37	May 21, 1792	32.8°N, 130.3°E	unknown	6.4 ± 0.2
38	Feb. 8, 1793	40.85°N, 139.95°E	unknown	6.9 - 7.1
39	June 29, 1799	36.6°N, 136.6°E	unknown	6.0 ± ¼
40	Nov. 18, 1802	35.2°N, 136.5°E	unknown	6.5 - 7.0
41	July 10, 1804	39.05°N, 139.95°E	unknown	7.0 ± 0.1
42	Sep. 25, 1810	39.9°N, 139.9°E	unknown	6.5 ± ¼
43	August 2, 1819	35.2°N, 136.3°E	unknown	7¼ ± ¼
44	Dec. 18, 1828	37.6°N, 138.9°E	unknown	6.9
45	August 19, 1830	35.1°N, 135.9°E	unknown	6.5 ± 0.2
46	Nov. 13, 1831	unknown	unknown	unknown
47	Dec. 7, 1833	38.9°N, 139.25°E	unknown	7½ ±¼
48	Feb. 9., 1834	43.4°N, 141.4°E	unknown	6.4
49	April 22, 1841	35.0°N, 138.5°E	unknown	6¼
50	April 25, 1843	42.0°N, 146.0°E	unknown	7.5
51	May 8, 1847	36.7°N, 138.2°E	unknown	7.4
52	May 13, 1847	37.2°N, 138.3°E	unknown	6½ ±¼
53	July 9, 1854	34.75°N, 136.0°E	unknown	7¼ ± ¼
54	Dec. 23, 1854	34.0°N, 137.8°E	unknown	8.4
55	Dec. 24, 1854	33.0°N, 135.0°E	unknown	8.4
56	March 15, 1855	unknown	unknown	unknown
57	Nov. 7, 1855	34.5°N, 137.75°E	unknown	7.0 - 7.5
58	Nov. 11, 1855	35.65°N, 139.8°E	unknown	6.9 ± 0.1
59	August 23, 1856	41.0°N, 142. ¼°E	unknown	7.5
60	July 14, 1857	34.8°N, 138.2°E	unknown	6¼ ±¼
61	April 9, 1858	36.4°N, 137.2°E	unknown	7.0 – 7.1
62	Jan. 5, 1859	34.8°N, 131.9°E	unknown	6.2 ± 0.2
63	March 14, 1872	35.15°N, 132.1°E	unknown	7.1 ± 0.2
64	July 22, 1887	37.5°N, 138.9°E	unknown	5.7
65	July 28, 1889	32.8°N, 130.65°E	unknown	6.3
66	Jan. 7, 1890	36.45°N, 137.95°E	unknown	6.2
67	Oct. 28, 1891	35.6°N, 136.6°E	unknown	8.0
68	Jan. 3, 1892	35.3°N, 137.1°E	unknown	5.5
69	Sep. 7, 1892	35.7°N, 137.0°E	unknown	6.1
70	Sep. 7, 1893	31.4°N, 130.5°E	unknown	5.3
71	Jan. 10, 1894	35.4°N, 136.7°E	unknown	6.3
72	June 20, 1894	35.7°N, 139.8°E	unknown	7.0
73	Oct. 22, 1894	38.9°N, 139.9°E	unknown	7.0
74	Jan. 18, 1895	36.1°N, 140.4°E	unknown	7.2
75	August 31, 1896	39.5°N, 140.7°E	unknown	7.2 ± 0.2
76	Jan. 17, 1897	36.65°N, 138.25°E	unknown	5.2
77	Feb. 20, 1897	38.1°N, 141.9°E	unknown	7.4
78	April 3, 1898	34.6°N, 131.2°E	unknown	6.2
79	April 23, 1898	38.6°N, 142.0°E	unknown	7.2
80	May 26, 1898	37.0°N, 138.9°E	unknown	6.1
81	August 10, 1898	33.6°N, 130.2°E	unknown	6.0
82	Sep. 1, 1898	24.5°N, 124.75°E	unknown	7
83	March 7, 1899	34.1°N, 136.1°E	unknown	7.0
84	August 9, 1901	40.5°N, 142.5°E	unknown	7.2
85	May 8, 1904	37.1°N, 138.9°E	unknown	6.1
86	June 2, 1905	34.1°N, 132.5°E	unknown	6.7
87	August 14, 1909	35.4°N, 136.3°E	unknown	6.8
88	March 15, 1914	39.5°N, 140.4°E	unknown	7.1
89	Dec. 8, 1922	32.7°N, 130.1°E	unknown	6.9
90	Sep. 1, 1923	35.2°N, 139.3°E	unknown	7.9
91	May 23, 1925	35.6°N, 134.8°E	unknown	6.8
92	July 4, 1925	35.5°N, 133.3°E	unknown	5.8
93	March 7, 1927	35.53°N, 135.15°E	0	7.3
94	August 6, 1927	37.93°N, 142.12°E	10	6.7
95	Oct. 27, 1927	37.5°N, 138.8°E	0	5.2
96	Oct. 17, 1930	36.30°N, 136.35°E	0	5.3
97	Nov. 26, 1930	35.1°N, 139.0°E	0	7.3
98	Sep. 21, 1931	36.15°N, 139.23°E	15	6.9
99	Sep. 21, 1933	37.1°N, 137.0°E	10	6.0
100	July 11, 1935	34.97°N, 138.42°E	0	6.4
101	Feb. 21, 1936	34.58°N, 135.72°E	40	6.4
102	Nov. 3, 1936	38.15°N, 142.13°E	0	7.5
103	May 1, 1939	40.13°N, 139.52°E	0	6.8
104	July 15, 1941	36.72°N, 138.23°E	0	6.1
105	March 4, 1943 March 5, 1943	35.43°N, 134.22°E 35.50°N, 134.22°E	0 0	6.2 6.2
106	Sep. 10, 1943	35.52°N, 134.08°E	0	7.2
107	Dec. 7, 1944	33.80°N, 136.62°E	30	7.9
108	Jan. 13, 1945	34.7°N, 137.0°E	0	6.8
109	Dec. 21, 1946	33.03°N, 135.62°E	20	8.0
110	Sep. 27, 1947	24.7°N, 123.2°E	95	7.4
111	June 28, 1948	36.17°N, 136.20°E	0	7.1
112	March 4, 1952	41.80°N, 144.13°E	0	8.2
113	March 7, 1952	36.48°N, 136.20°E	0	6.5
114	July 27, 1955	33.73°N, 134.32°E	10	6.4
115	Oct. 19, 1955	40.27°N, 140.18°E	0	5.9
116	Feb. 2, 1961	37°27′N, 138°50′E	20	5.2
117	Feb. 27, 1961	31°36′N, 131°51′E	40	7.0
118	April 23, 1962	42°14′N, 143°55′E	60	7.0
119	April 30, 1962	38°44′N,141°08′E	0	6.5
120	May 7, 1964	40°23′N,139°00′E	0	6.9
121	June 16, 1964	38°21′N, 139°11′E	40	7.5
122	Feb. 21, 1968	32°01′N,130°43′E	0	6.1
123	April 1, 1968	32°17′N, 132°32′E	30	7.5
124	May 16, 1968	40°44′N, 143°35′E	0	7.9
125	June 17, 1973	42°58′N, 145°57′E	40	7.4
126	Jan. 14, 1978	34°46′N, 139°15′E	0	7.0
127	Feb. 20, 1978	38°45′N, 142°12′E	50	6.7
128	June 12, 1978	38°09′N, 142°10′E	40	7.4
129	March 21, 1982	42°04′N, 142°36′E	40	7.1
130	May 26, 1983	40°21.4′N, 139°04.6′E	14	7.7
131	June 21, 1983	41°15.7′N, 139°00.2′E	6	7.1
132	Dec. 17, 1987	35°22.3′N, 140°29.8′E	58.0	6.7
133	Jan. 15, 1993	42°55.0′N, 144°21.4′N	101	7.8
134	Feb. 7, 1993	37°39.2′N, 137°18.0′N	25	6.6
135	July 12, 1993	42°46.8′N, 139°11.0′E	35	7.8
136	Oct. 4, 1994	43°22.3′N, 147°42.5′E	23	8.1
137	Dec. 28, 1994	40°25.6′N, 143°44.9′E	0	7.5
138	Jan. 17, 1995	34°35.7′N, 135°02.2′E	17.9	7.2
139	March 26, 1997	31°59′N, 130°22′E	8	6.3
140	May 13, 1997	31°57′N, 130°18′E,	8	6.2

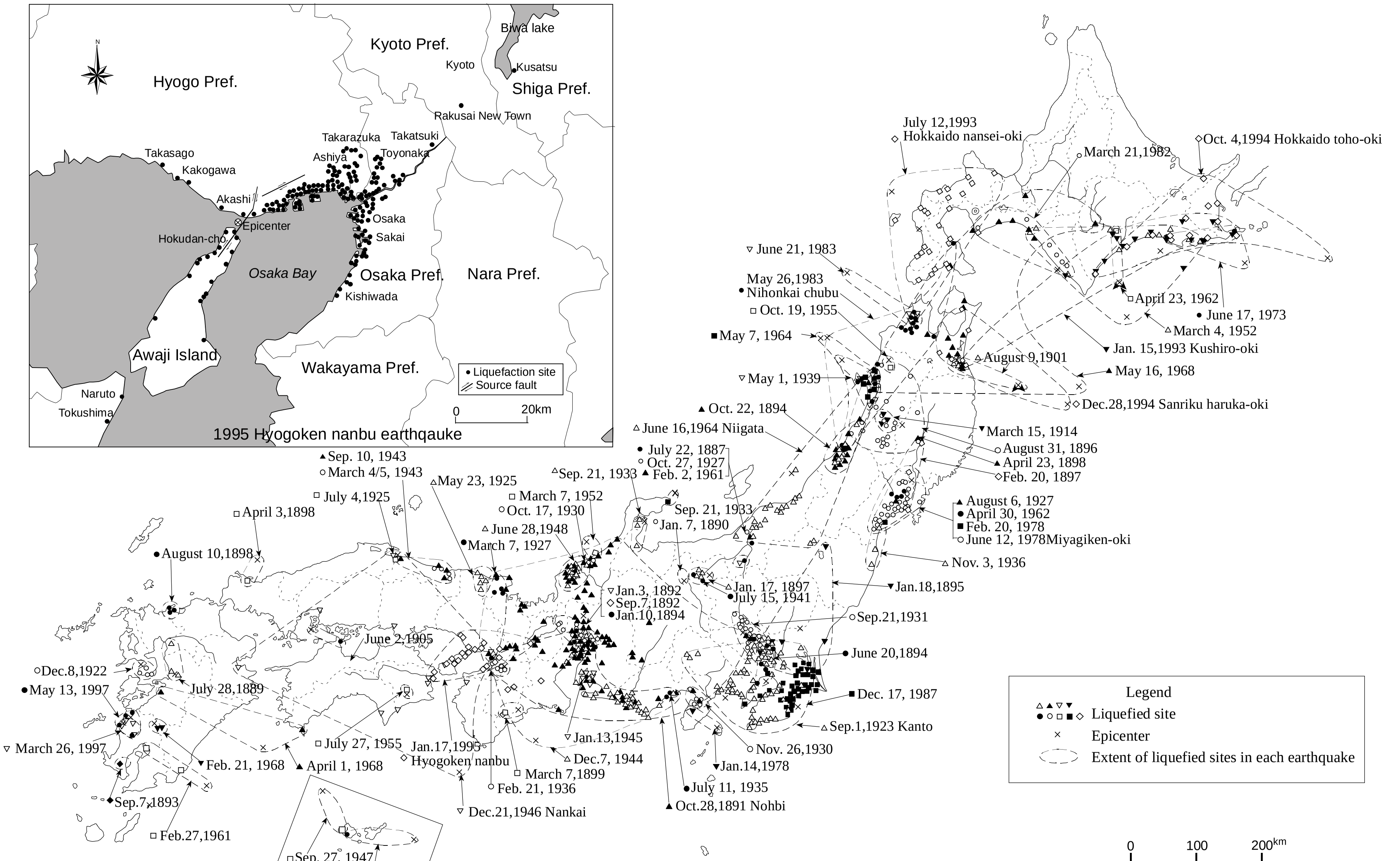

Figure 1: Liquefied sites during the period of 1885-1997

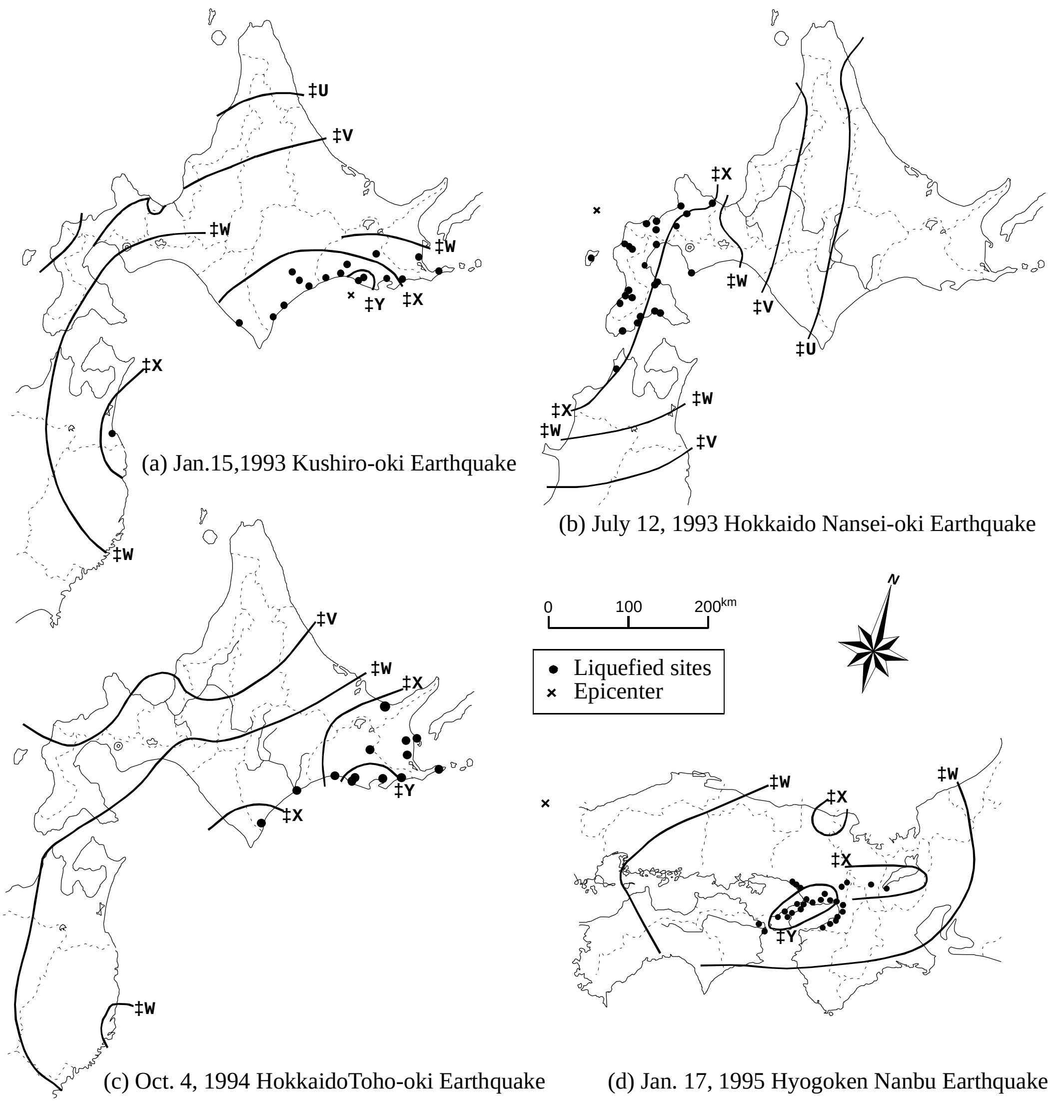

Figure 2: Distribution of liquefied sites and Seismic Intensity

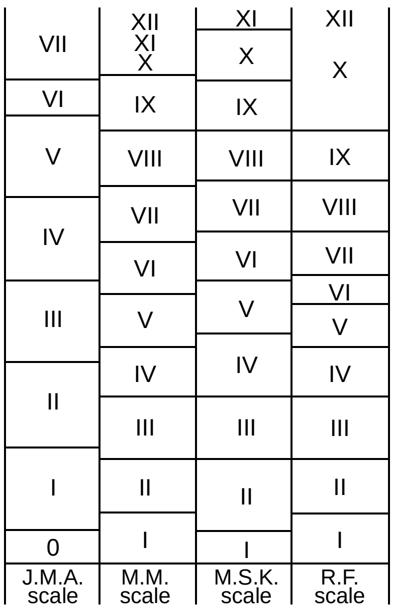

Figure 3: Comparison of different seismic intensity scales [Seismological Division, J.M.A., 1971]

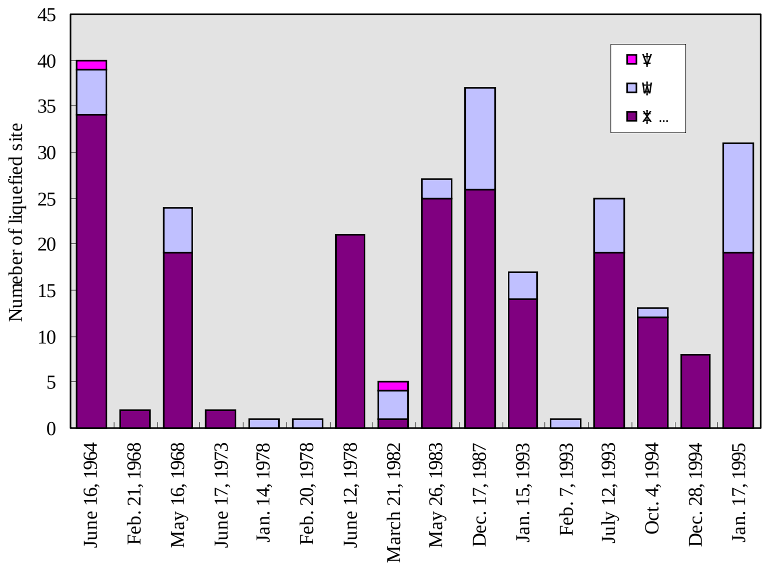

Figure 4: Seismic intensity at liquefied sites on the J.M.A. scale

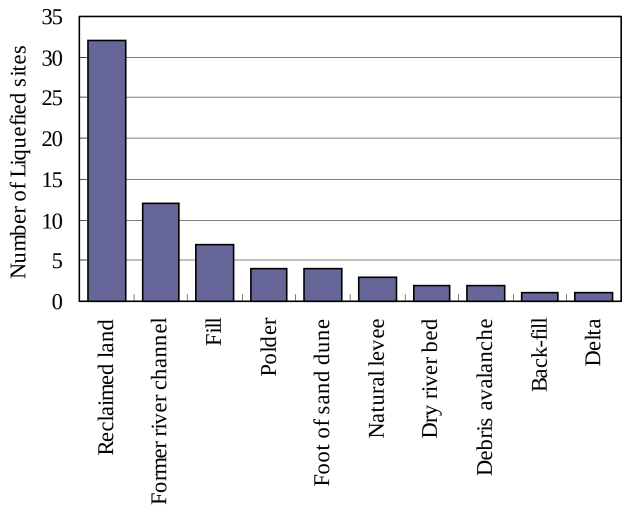

Figure 5: Geomorphological conditions at sites where liquefaction occurred at less than V

MAXIMUM EPICENTRAL DISTANCES TO A LIQUEFIED SITE

The maximum extent of the liquefaction susceptible area also can be estimated directly from the relationship between an earthquake magnitude and epicentral distance to farthest liquefied sites. Kuribayashi and Tatsuoka [1975] have shown, for 32 historic Japanese earthquakes, that the farthest epicentral distance to a liquefied sites, *R* in km, is bounded by a straight line on a magnitude, M_J, versus logarithm of distance plot, which can be expressed as follows:

$$\log R = 0.77 M_J - 3.6 \quad (1)$$

where M_J is the earthquake magnitude as defined using the J. M. A. scale.

Ambraseys [1988] also proposed a similar bound for shallow focus earthquakes based on more extensive study of epicentral distances at which liquefaction has occurred for 137 earthquakes including 32 and 27 events from Kuribayashi and Tastuoka [1975] and from other previous investigations [Youd, 1977; Davis and Berrill, 1983; Davis and Berrill, 1984; Fairless; Berrill, 1984] respectively.

The works of Kuribayashi and Tatsuoka [1975] was recently supplemented by the author with new data from 67 Japanese earthquakes over the past 106 years, including the original 32 earthquakes studied by Kuribayashi and Tatsuoka [Wakamatsu, 1991]. As a result of this study, the author proposed an upper bound relationship between M_J and R (for $M_J > 5.0$) as follows:

$$\log R = 2.22 \log(4.22 M_J - 19.0) \tag{2}$$

The bounds developed by the author as well as Kuribayashi and Tatsuoka are plotted in Figure 6. The bound given by Eq. (2) based on the author's work is too conservative in practice. This is because the definition of liquefaction used by the author includes even minor signs of liquefaction effects such as minor sand boils. Considering only those data (from 46 Japanese events) indicating significant liquefaction gives a less pessimistic bound (the broken line in Figure 6) [Wakamatsu, 1993]:

$$\log R = 3.5 \log(1.4 M_J - 6.0) \tag{3}$$

The M_J versus R for farthest sites of minor signs of liquefaction effects in the recent earthquakes after 1990 and a new data for the May 26, 1983 Nihonkai Chubu earthquake are also plotted in Figure 6. All of the sites fall within the upper bound relationship given by Eq. (2), which indicates that this relationship is valid for the prediction of the maximum range of liquefaction for a particular magnitude of earthquake, given the presence of potentially liquefiable Holocene sediments.

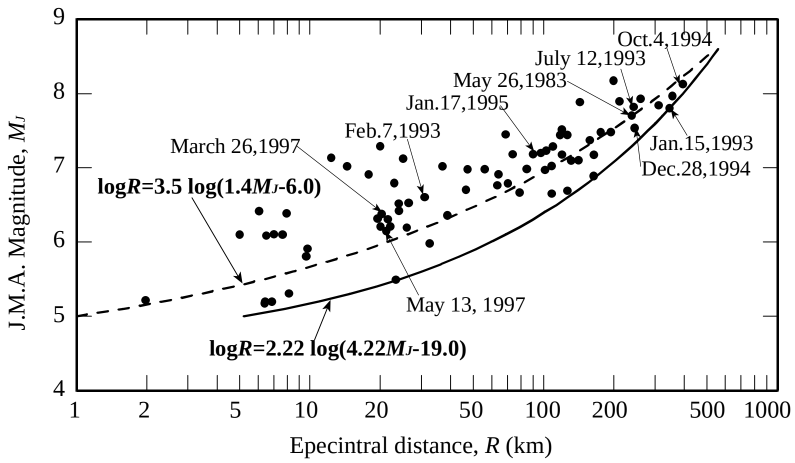

Figure 6: Epicentral distance to farthest liquefied sites, *R*, for J.M.A. Magnitude, M_J

CONCLUSIONS

The following can be summarized from the case histories of liquefaction due to the earthquakes occurred in Japan from 416 to 1997.

(1) A total of 140 events with magnitudes ranging from 5.2 to 8.4 have induced liquefaction during the period of 416-1997.

(2) Several thousand sites of liquefaction appeared in most part of Japan due to the 140 earthquakes. The most of them are located on low-lying areas underlain by liquefiable Holocene sediments.

(3) Liquefaction was observed in more than five successive earthquakes in the last fifteen centuries, respectively, in such areas as the plains of Nohbi, Akita, Niigata, Kanto, Osaka, Kanazawa, Tsugaru, Tokachi, Sendai, Takada, Shizuoka and Tenryu, and Kyoto Basin.

(4) The liquefaction was induced by seismic shaking with an intensity V and greater on the J.M.A. scale. However, minor cases of liquefaction occurred at less than V.

(5) The upper bound relationship between earthquake magnitude on the J.M.A. scale, M_J, and epicentral distance to the farthest liquefied site, R, given by $\log R = 2.22 \log(4.22 M_J - 19.0)$ is valid for the prediction of the maximum range of liquefaction for a particular magnitude of earthquake.

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