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DEVELOPMENT OF GIS DATABASE FOR HISTORIC LIQUEFACTION SITES IN JAPAN

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ABSTRACT

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. Thus 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 then, extensive liquefaction has been observed during more than a dozen earthquakes including the 1995 Hyogoken-nambu (Kobe) earthquake. The author has supplemented the previous work with data from the earthquakes since 1991 as well as newly found data for the earthquakes before 1990, and digitized the sites of liquefaction into a GIS database. The database is useful not only to improve the site-specific methods employed to evaluate whether soils will liquefy in future earthquakes but also to develop a better understanding of the geotechnical and geologic nature of liquefiable materials. This paper introduces an outline of the database: 147 earthquakes that induced liquefaction are listed, distribution of approximately 16,000 liquefaction sites during the earthquakes throughout Japan are presented, and some characteristics of liquefaction occurrences in Japan are discussed.

Keywords: liquefaction site, liquefaction field case history databases, GIS (Geographical Information System) database

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 (e.g. Kuribayashi and Tatsuoka, 1975; Youd, 1984; Yasuda and Tohno, 1988; Wakamatsu, 1991). Thus, 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 then, extensive liquefaction has been observed during more than a dozen earthquakes including the 1995 Hyogoken-nambu (Kobe) earthquake. In addition, new data have been found on historical earthquakes before 1990. Thus the author supplements the previous work by Wakamatsu (1991) with new data for the earthquakes since 1991 as well as the earthquakes before 1990, and digitized the sites of liquefaction into a GIS database. The database will be useful not only to improve the site-specific methods employed to evaluate whether soils will liquefy in future earthquakes but also to develop a better understanding of the geotechnical and geologic nature of liquefiable materials. This paper introduces an outline of the database and discusses some characteristics of liquefaction occurrences in Japan.

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IDENTIFICATION OF LIQUEFACTION OCCURRENCES

To search for records of liquefaction effects, various kinds of materials on earthquake damage, such as reports, papers, web site contents, and ancient documents for all of Japan, were collected. Descriptions of liquefaction effects were picked up from these documents, and the sites where liquefaction took place were identified based on these descriptions. In addition, in several earthquakes the author conducted post-earthquake reconnaissance investigations, aerial photo interpretation, and interviews with 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, lateral spreading, ground subsidence, and settlement of structures without sand and/or water boiling were excluded from the signs of liquefaction effect.

EARTHQUAKES THAT CAUSED LIQUEFACTION

Up to the present, approximately 1,000 destructive earthquakes have been recorded in various kinds of historical materials and seismic data in Japan (Usami, 2003). The oldest of the earthquakes is the earthquake of August 23, 416, which was documented in the "Nihon Shoki", an authorized historical document of Japan. These 1,000 earthquakes during the period of 416–2006 in Japan were investigated in this study. They include about 500 earthquakes prior to 1884, which are documented in nonscientific materials, and more than 500 recent earthquakes that took place after 1884, when nationwide earthquake observation was started in Japan. Instances of liquefaction evidence such as sand dike in the ground, which were revealed by archeological excavation, are excluded from the liquefaction sites in this study, for the dates of earthquakes that induced liquefaction can be difficult to identify.

The investigation revealed that a total of 147 events have induced liquefaction at a total of 16,082 sites from 416 to 2006, including the original 123 earthquakes previously presented by the author. These 147 earthquakes are summarized in Table 1. The JMA (Japan Meteorological Agency) magnitude, M_J, of the earthquakes that induced liquefaction ranges from 5.2 to 8.6. The oldest event that was identified to induce liquefaction is the 745 earthquake that occurred in Gifu Prefecture, located in the central part of the main island of Japan, whereas the latest one is the Miyagiken-oki earthquake of August 16, 2005, which attacked the Sendai area in the northern part of the main island of Japan. Since 1884, when systematic earthquake observation began in Japan, 87 earthquakes have generated liquefaction. Thus liquefaction has occurred approximately twice in every three years somewhere in Japan during the last 123 years.

In the Table, the number of liquefaction sites in every earthquake is also listed; the total number of liquefaction sites in all 147 earthquakes reached 16,082. It is especially large, 8083 and 1770, for No. 135, the earthquake of January 17, 1995, in Hyogoken-nambu, and No. 144, the earthquake of October 23, 2004, in Niigata-ken Chuetsu, respectively. This is because the liquefaction data for these earthquakes are especially complete as they contain the results of detailed surveys obtained by the interpretation of aerial photographs taken immediately after the earthquake, as well as because of the strong ground motion intensity and liquefaction susceptibility of the subsurface soil deposits in the affected areas.
Earthquakes Nos. 52 and 53 occurred on Dec. 23 and 24 of the same year, in quick succession; therefore it is difficult to identify which shock triggered the occurrence of the liquefaction in some areas located between the epicenters of the two earthquakes. Thus liquefaction sites during these earthquakes were combined in the database, and the number of the sites for the two earthquakes are counted as a single total in Table 1.

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Table 1. Earthquakes which Induced Liquefaction during the Period of 416–2006

No.	Date	JMA magnitude	Location, lat.(°N), long.(°E)		Depth (km)	Earthquake name Epicentral region	Number of liquefaction sites**
1	n.d., 745	7.9*	35.2	136.6	-		(1)
2	n.d., 850	7.0*	39.0	139.7	-		(1)
3	July 10, 863	-	-	-	-		(1)
4	August 13, 1185	7.4*	35.00	135.80	-		1
5	Oct. 9, 1257	7.3*	35.20	139.50	-		1
6	May 13, 1449	6.1*	35.00	135.75	-		(1)
7	July 9, 1498	7.3*	33.00	132.25	-		(1)
8	Jan. 18, 1586	6.1*	35.00	135.75	-		(1)
9	Sep.1, 1596	7.0*	33.30	131.60	-		(1)
10	Sep.5, 1596	7.5*	34.80	135.40	-		1
11	Feb. 3, 1605	7.9	33.50	138.50	-	Keicho	1
12	March 1, 1633	7.0*	35.20	139.20	-		1
13	Oct. 18, 1644	6.5*	39.40	140.00	-		1
14	June 16, 1662	7.4*	35.30	135.90	-		3
15	Feb. 1, 1666	6.8*	37.10	138.20	-		1
16	Oct. 7, 1685	-	-	-	-		1
17	June 19, 1694	7.0*	40.20	140.10	-		10
18	Dec. 12, 1694	-	-	-	-		1
19	Dec. 31, 1703	8.1*	34.70	139.80	-	Genroku	3 (4)
20	May 27, 1704	7.0*	40.40	140.00	-		1
21	Oct. 28, 1707	8.6	33.20	135.90	-	Houei	7
22	May 13, 1717	7.5*	38.50	142.50	-		1
23	n.d.1717	6.3*	36.50	136.50	-		(1)
24	Dec. 19, 1723	6.5*	32.90	130.60	-		1
25	March 8, 1729	-	-	-	-		1
26	n.d.,1734	-	-	-	-		(1)
27	Jan. 3, 1738	5,5*	37.00	138.7	-		(1)
28	March 26, 1751	5.8*	35.00	135.80	-		(1)
29	May 21, 1751	7.2*	37.10	138.20	-		2
30	Oct. 31, 1762	7.0*	38.10	138.70	-		3
31	March 8, 1766	7.3*	40.70	140.50	-		4
32	Aug. 29, 1769	7.8*	33.00	132.10	-		1
33	June 11, 1774	-	-	-	-		1
34	August 23, 1782	7.0*	35.40	139.10	-		1
35	May 21, 1792	6.4*	32.80	130.30	-		1
36	Feb. 8, 1793	7.0*	40.85	139.95	-		3
37	June 29, 1799	6.0*	36.60	136.70	-		3
38	Nov. 18, 1802	6.8*	35.20	136.50	-		(1)
39	July 10, 1804	7.0*	39.05	139.95	-	Kisakata	37 (4)
40	Sep. 25, 1810	6.5*	39.90	139.90	-		1
41	August 2, 1819	7.3*	35.20	136.30	-		5
42	Dec. 18, 1828	6.9	37.60	138.90	-		55
43	August 19, 1830	6.5*	35.10	135.60	-		2
44	Nov. 13, 1831	-	-	-	-		(1)
45	Dec. 7, 1833	7.5*	38.90	139.25	-		1
46	Feb. 9., 1834	6.4*	43.30	141.40	-		1
47	April 22, 1841	6.3*	35.00	138.50	-		2
48	April 25, 1843	7.5*	42.00	146.00	-		1
49	May 8, 1847	7.4	36.70	138.20	-	Zenkohji	52 (10)

Table 1. Earthquakes which Induced Liquefaction during the Period of 416–2006 (cont.)

No.	Date	JMA magnitude	Location, lat.(°N), long.(°E)		Depth (km)	Earthquake name Epicentral region	Number of liquefaction sites**
50	May 13, 1847	6.5*	37.20	138.30	-		3
51	July 9, 1854	7.3*	34.75	136.10	-		26 (1)
52	Dec. 23, 1854	8.4	34.00	137.80	-	Ansei Tokai	84 (8)
53	Dec. 24, 1854	8.4	33.00	135.00	-	Ansei Nankai	
54	March 15, 1855	-	-	-	-		1
55	Nov. 7, 1855	7.3*	34.50	137.75	-		6
56	Nov. 11, 1855	7.1*	35.65	139.80	-	Edo	12 (1)
57	August 23, 1856	7.5*	41.00	142.50	-		1
58	April 9, 1858	7.1*	36.40	137.20	-		123
59	Jan. 5, 1859	6.2*	34.80	131.90	-		1
60	March 14, 1872	7.1*	35.15	132.10	-	Hamada	53
61	July 22, 1887	5.7	37.50	138.90	-	Koshi-gun	(1)
62	July 28, 1889	6.3	32.80	130.65	-	Kumamoto	1
63	Jan. 7, 1890	6.2	36.45	137.95	-	Saigawa-ryuiki	1
64	Oct. 28, 1891	8.0	35.60	136.60	-	Nohbi	227 (18)
65	Jan. 3, 1892	5.5	35.30	137.10	-	Aftershock of of Nohbi	3
66	Sep. 7, 1892	6.1	35.70	137.00	-	Aftershock of of Nohbi	(1)
67	Sep. 7, 1893	5.3	31.40	130.50	-	Chiran	1
68	Jan. 10, 1894	6.3	35.40	136.70	-	Aftershock of of Nohbi	87
69	June 20, 1894	7.0	35.70	139.80	-	Tokyo-wan Hokubu	27 (1)
70	Oct. 22, 1894	7.0	38.90	139.90	-	Shonai	50
71	Jan. 18, 1895	7.2	36.10	140.40	-	Kasumigaura-fukin	6
72	August 31, 1896	7.2*	39.50	140.70	-	Riku-u	48 (2)
73	Jan. 17, 1897	5.2	36.65	138.25	-	Naganoken hokubu	16
74	Feb. 20, 1897	7.4	38.10	141.90	-	Sendai-oki	4
75	April 3, 1898	6.2	34.60	131.20	-	Mishima	1
76	April 23, 1898	7.2	38.60	142.00	-	Miyagiken-oki	1
77	May 26, 1898	6.1	37.00	138.90	-	Miyagiken-oki	1
78	August 10, 1898	6.0	33.60	130.20	-	Fukuoka	10
79	Sep. 1, 1898	7*	24.50	124.75	-	Yaeyama-gunto	(1)
80	March 7, 1899	7.0	34.10	136.10	-	Kii-hanto nanseibu	1
81	August 9, 1901	7.2	40.50	142.50	-	Aomoriken-oki	8
82	May 8, 1904	6.1	37.10	138.90	-	Muikamachi	1
83	June 2, 1905	7.2	34.10	132.50	-	Geiyo	1
84	August 14, 1909	6.8	35.40	136.30	-	Gohno (Anegawa)	120
85	March 15, 1914	7.1	39.50	140.40	-	Akita Senpoku	3
86	Dec. 8, 1922	6.9	32.70	130.10	-	Chijiwa-wan	4
87	Sep. 1, 1923	7.9	35.33	139.14	23.0	Kanto	850
88	May 23, 1925	6.8	35.56	134.84	0.0	Kita-Tajima	15
89	July 4, 1925	5.7	35.35	133.42	0.0	Miho-wan	2
90	March 7, 1927	7.3	35.63	134.93	20.0	Kita-Tango	19
91	August 6, 1927	6.7	37.90	142.17	25.0	Miyagiken-oki	1
92	Oct. 27, 1927	5.2	37.50	138.85	0.0	Sekihara	1
93	Oct. 17, 1930	6.3	36.30	136.35	0.0	Daishoji	2
94	Nov. 26, 1930	7.3	35.04	138.98	2.0	Kita-Izu	7
95	Sep. 21, 1931	6.9	36.16	139.28	0.0	Nishi-Saitama	127
96	Sep. 21, 1933	6.0	37.12	136.83	30.0	Noto-hanto	6
97	July 11, 1935	6.4	35.01	138.40	9.0	Shizuoka	10
98	Feb. 21, 1936	6.4	34.49	135.72	19.0	Kawachi-Yamato	14

Table 1. Earthquakes which Induced Liquefaction during the Period of 416–2006 (cont.)

99	Nov. 3, 1936	7.5	36.26	142.07	61.0	Kinkazan-oki	3
100	May 1, 1939	6.8	39.94	139.75	2.0	Oga	14 (1)
101	July 15, 1941	6.1	36.68	138.15	7.0	Nagano	9
102	March 4, 1943	6.2	35.44	134.14	2.0	Tottori-oki	12
103	Sep. 10, 1943	7.2	35.47	134.19	0.0	Tottori	90
104	Dec. 7, 1944	7.9	33.57	136.18	40.0	Tohnankai	478 (1)
105	Jan. 13, 1945	6.8	34.70	137.11	10.0	Mikawa	156
106	Dec. 21, 1946	8.0	32.93	135.85	24.0	Nankai	43 (1)
107	Sep. 27, 1947	7.4	24.70	123.20	95.0	Ishigakijima	1
108	June 28, 1948	7.1	36.17	136.30	0.0	Fukui	170 (1)
109	March 4, 1952	8.2	41.80	144.13	0.0	Tokachi-oki	15
110	March 7, 1952	6.5	36.48	136.20	0.0	Daishoji-oki	2
111	July 27, 1955	6.4	33.73	134.32	10.0	Tokushimaken nanbu	1
112	Oct. 19, 1955	5.9	40.27	140.18	0.0	Futatsui	1
113	Feb. 2, 1961	5.2	37.45	138.84	0.0	Nagaoka	3
114	Feb. 27, 1961	7.0	31.64	131.89	37.0	Hyuganada	2
115	April 23, 1962	7.1	42.46	143.77	69.0	Hiroo-oki	2
116	April 30, 1962	6.5	38.74	141.14	19.0	Miyagiken hokubu	7
117	May 7, 1964	6.9	40.39	138.67	24.0	Ogahanto-oki	18
118	June 16, 1964	7.5	38.37	139.22	23.0	Niigata	268 (1)
119	Feb. 21, 1968	6.1	32.02	130.72	0.0	Ebino	2
120	April 1, 1968	7.5	32.28	132.53	0.0	Hyuganada	3
121	May 16, 1968	7.9	40.73	143.58	20.0	Tokachi-oki	78
122	June 17, 1973	7.4	42.97	145.95	25.0	Nemurohanto-oki	5
123	Jan. 14, 1978	7.0	34.77	139.25	0.0	Izu-Ohshima kinkai	1
124	Feb. 20, 1978	6.7	38.75	142.20	0.0	Miyagiken-oki	1
125	June 12, 1978	7.4	38.15	142.17	2.0	Miyagiken-oki	52
126	March 21, 1982	7.1	42.07	142.60	0.0	Urakawa-oki	22
127	May 26, 1983	7.7	40.36	139.08	30.0	Nihonkai chubu	335 (1)
128	June 21, 1983	7.1	41.26	139.00	9.0	After shock, Nihonkai chubu	8
129	Dec. 17, 1987	6.7	35.37	140.50	19.0	Chibaken toho-oki	331
130	Jan. 15, 1993	7.5	42.92	144.36	61.0	Kushiro-oki	303
131	Feb. 7, 1993	6.6	37.65	137.30	2.0	Notohanto-oki	76
132	July 12, 1993	7.8	42.78	139.18	7.0	Hokkaido-nansei-oki	506
133	Oct. 4, 1994	8.2	43.37	147.68	2.0	Hokkaido-toho-oki	198 (4)
134	Dec. 28, 1994	7.6	40.43	143.75	0.0	Sanriku-haruka-oki	90
135	Jan. 17, 1995	7.3	34.60	135.04	40.0	Hyogoken-nambu (Kobe)	8,083
136	March 26, 1997	6.6	31.97	130.36	10.0	Kagoshimaken hokuseibu	20 (2)
137	May 13, 1997	6.4	31.94	130.31	24.0	Kagoshimaken hokuseibu	11
138	Feb. 26, 1999	5.3	39.15	139.84	95.0	Akitaken-oki	8
139	Oct. 06, 2000	7.3	35.27	133.35	0.0	Tottoriken-seibu	418
140	March, 24, 2001	6.7	34.13	132.70	0.0	Geiyo	34
141	May, 26, 2003	7.1	38.82	141.65	0.0	Miyagiken-oki	27
142	July, 26. 2003	6.4	38.43	141.17	10.0	Miyagiken-hokubu	29
143	Sept. 26, 2003	8.0	41.78	144.08	0.0	Tokachi-oki	148
144	Oct. 23, 2004	6.8	37.29	138.87	0.0	Niigata-ken Chuetsu	1,770
145	Nov. 29. 2004	7.1	42.15	145.05	37.0	Kushiro-oki	3
146	March 20, 2005	7.0	33.12	130.03	69.0	Fukuokaken seiho-oki	88
147	Aug. 16, 2005	7.2	38.15	142.28	19.0	Miyagiken-oki	15

-: earthquake focal depth is unknown
*: mean value of the estimated range of the earthquake magnitude
**: Numbers in parentheses represent liquefaction sites for which detailed information is not available.

LIQUEFACTION DATABASE FOR ALL OF JAPAN

The liquefaction data whose locations could be identified were mapped and digitized using GIS software. The data set contains the coordinates, place name, and source reference for each liquefaction site and the date, magnitude, epicenter, and focal depth of the earthquake that induced the liquefaction.

Figure 1 plots liquefaction sites attributed to all 147 earthquakes for which locations of liquefaction could be identified. Except in a few cases, the liquefaction sites are located on low-lying areas whose subsurface ground consists of Holocene alluvial deposits or artificial fills. In some areas, such as Tokyo, Nagoya Akita, and Niigata, liquefaction has been observed in more than five successive earthquakes up to the present.

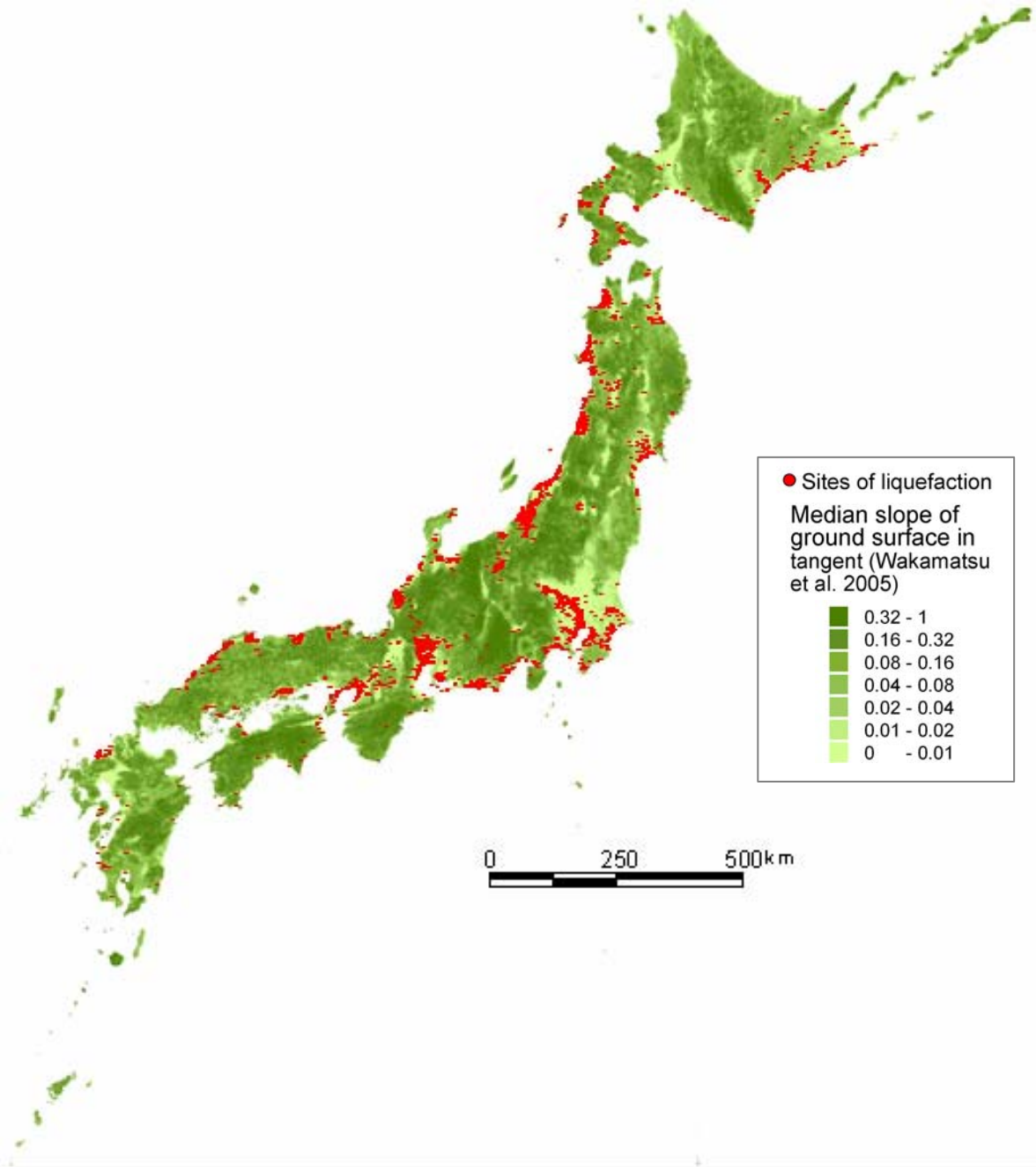


Figure 1. Distribution of liquefaction sites during 416–2006

Figure 2 shows the distribution of liquefaction sites in the Tokyo metropolitan area; liquefaction was observed during six successive earthquakes: the 1855 Edo (M_J 7.1), the 1894 Tokyo-wan hokubu (M_J7.0), the 1895 Kasumigaura (M_J 7.2), the 1923 Kanto (M_J 7.9), the 1931 Nishi-Saitama (M_J 6.9), and the 1987 Chibaken Toho-oki (M_J 6.7). The liquefaction sites are distributed along the river and coast in flat and low-lying areas

SEISMIC INTENSITY AT LIQUEFACTION SITES

The extent of liquefaction in a 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 3 shows several examples of distributions of liquefaction sites and seismic intensities on the JMA scale during the earthquakes in the Tokyo metropolitan area. The correlation of different seismic intensity scales including JMA and other intensity scales are shown in Figure 4. Most of the liquefaction sites in each earthquake are located within the zones of JMA intensity V and greater, which is almost equivalent to VIII on the Modified Mercalli (M.M.) scale. However, minor cases of liquefaction occurred at intensities lower than V. The subsurfaces of the sites where liquefaction occurred at intensities lower than V presumably consist of the deposits most susceptibleto liquefaction, although the earthquake shaking of these sites may be locally stronger.

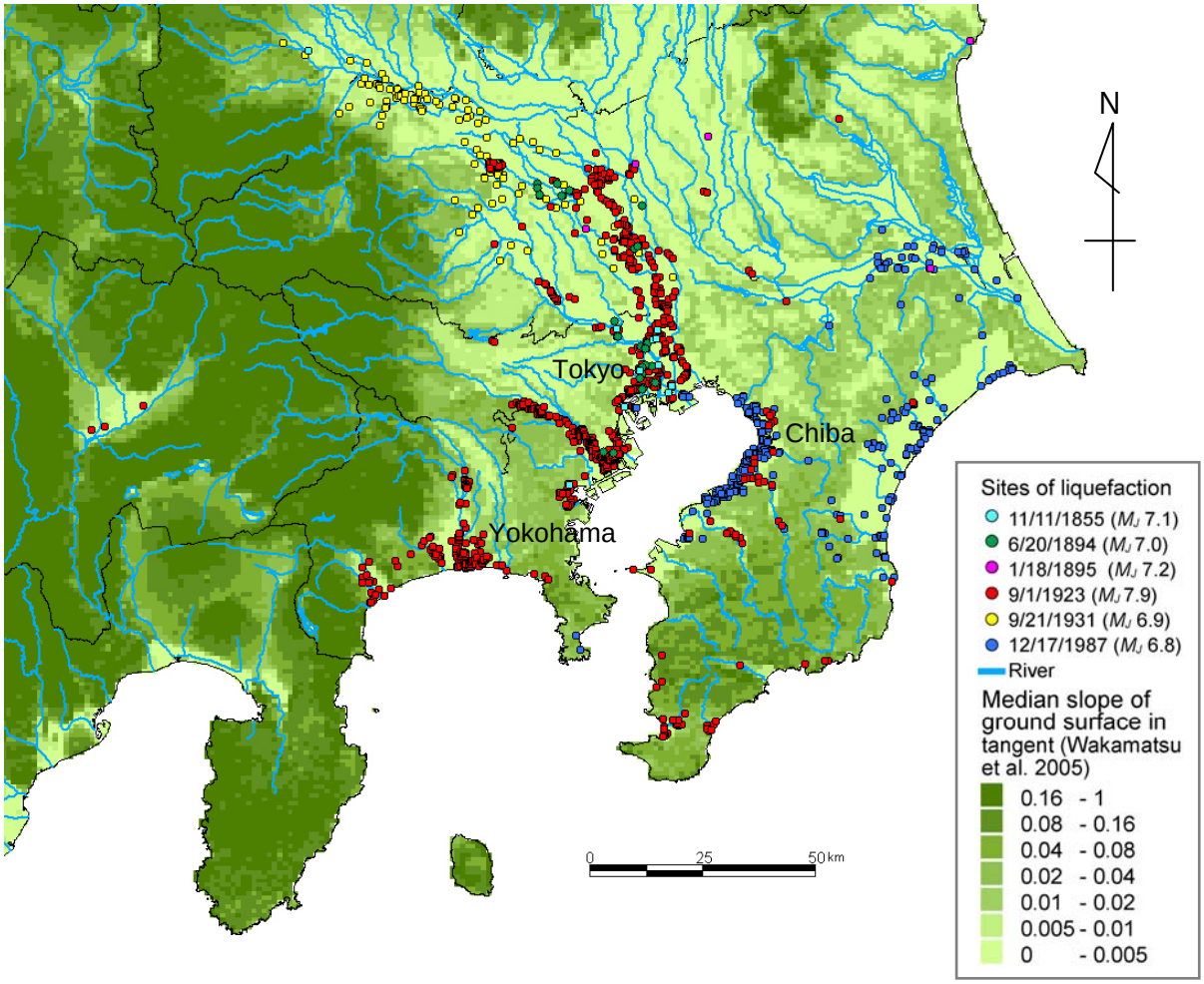
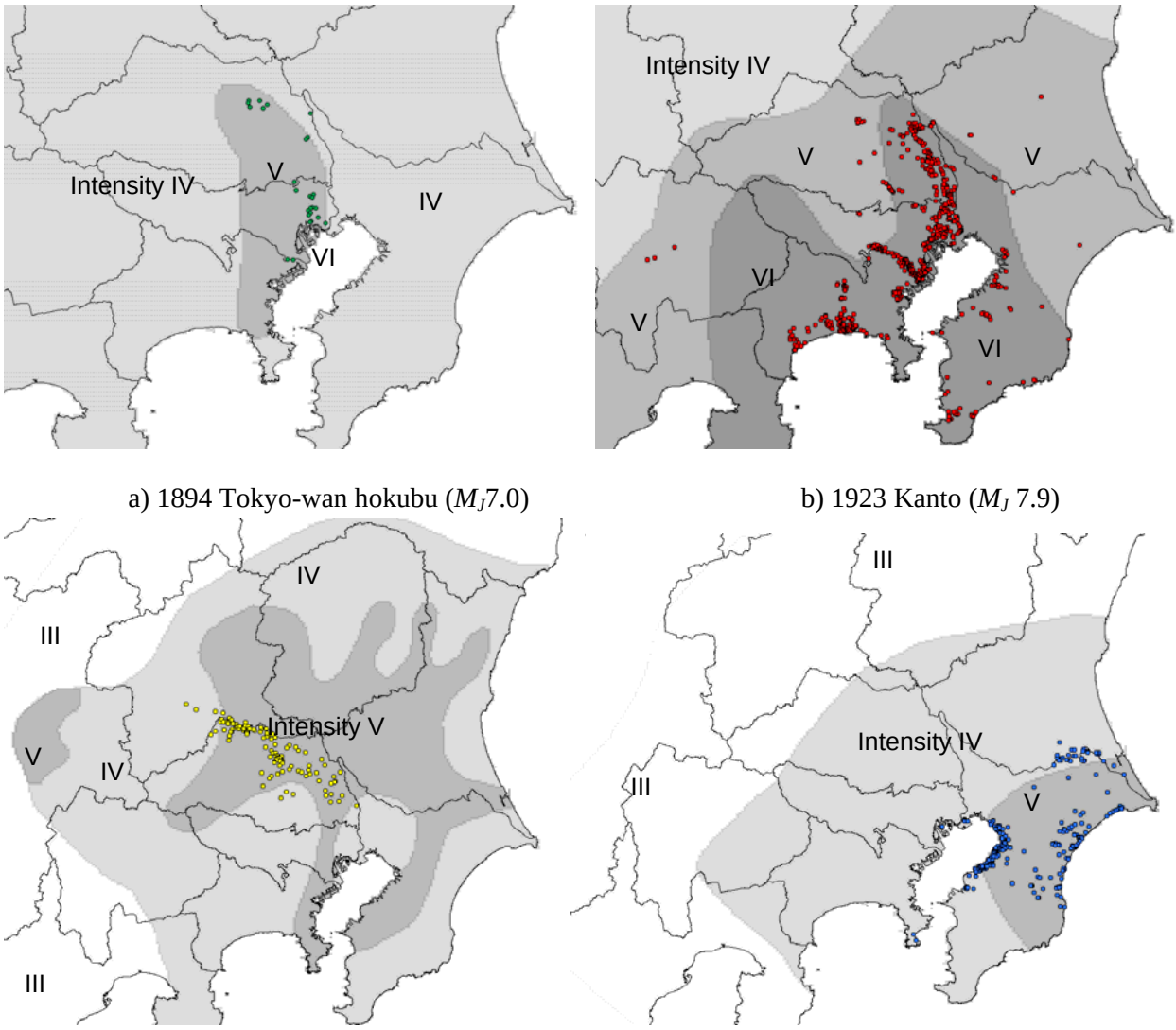


Figure 2. Liquefaction sites during the past earthquakes in Tokyo metropolitan area



a) 1894 Tokyo-wan hokubu (M_J7.0)

b) 1923 Kanto (M_J 7.9)

c) 1931 Nishi-Saitama (M_J 6.9)

d) 1987 Chibaken Toho-oki (M_J 6.7)

Figure 3. : **Distribution of seismic intensity (after Usami, 2003) and liquefaction sites**

J.M.A. scale	M.M. scale	M.S.K. scale	R.F. scale
VII	XII	XI	XII
	XI	X	X
	X		
VI	IX	IX	
V	VIII	VIII	IX
IV	VII	VII	VIII
	VI	VI	VII
III	V	V	VI
			V
II	IV	IV	IV
	III	III	III
I	II	II	II
0	I	I	I

Figure 4. Correlation of different seismic intensity scales (Seismological Division, JMA, 1971)

CONCLUDING REMARKS

Liquefaction sites during the past earthquakes were investigated for all of Japan and digitized into a GIS database. The investigation revealed that: a total of 147 events with magnitudes ranging from 5.2 to 8.6 have induced liquefaction during the past approximately 16 centuries; approximately 16,000 sites of liquefaction appeared in most parts of Japan due to the earthquakes; most of them are located on low-lying areas underlain by liquefiable Holocene sediments and artificial fills; and the liquefaction in area around Tokyo was induced by seismic shaking with an intensity of V and greater on the JMA scale.

Currently, the contents and format of the database are being checked and adjusted. The database will be released on the Internet and/or on CD-ROM in the future. The database will be useful not only to improve the site-specific methods employed to evaluate whether soils will liquefy in future earthquakes but also to developing a better understanding of the geotechnical and geologic nature of liquefiable materials.

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