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HISTORY OF EARTHQUAKE-INDUCED
SOIL LIQUEFACTION IN JAPAN

JAN 1977

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HISTORY OF EARTHQUAKE-INDUCED
SOIL LIQUEFACTION IN JAPAN

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ABSTRACT

To correlate the actual liquefaction phenomena and site conditions, a literature survey on liquefaction phenomena brought by earthquakes during the last century in Japan was performed. Liquefaction distribution map of Japan and the regional maps of Kanto, Nobi and Hokuriku are presented and factors affecting the occurrence of liquefaction are discussed. In the last century liquefaction in subsoils has been observed at some hundred sites during 44 earthquakes and the sites were limited only to alluvial deposits and reclaimed lands. Furthermore, it was found in several zones that liquefaction occurred repeatedly by consecutive earthquakes. Estimated JMA intensity scale at liquefied sites was equal to or higher than the fifth grade which corresponds to the maximum accelerations of 80 to 250 gals or higher. The extent of liquefied zones is limited to a certain area depending on the magnitudes of earthquakes.

Key words: alluvial deposits, earthquakes, earthquake damage, earthquake resistance, soil liquefaction, seismic disaster

INTRODUCTION

During of the past major earthquakes many structural damages were caused by settlement or tilting of structures due to liquefaction of saturated sandy subsoils. In accordance with prediction of liquefaction potential of subsoils, number of research efforts have been expended by means of laboratory tests and in-situ tests. Meanwhile, correlations between the actual liquefaction phenomena and site conditions have been investigated only a little with regard to limited areas and periods. So far, reviews of the correlation of liquefaction have been performed at several sites in Japan (Miyabe, 1933, Kishida, 1969, Ishihara, 1974, and Iida, (1974). In view of many interesting facts in these reviews, further investigation of this subject would be expected. This report contributes to this subject through a literature survey of liquefaction phenomena brought by earthquakes during the last century in Japan.

Liquefaction distribution maps since 1872 is presented firstly and the factors relating to liquefaction are discussed. In the literatures on earthquakes which brought damage during the past several centuries, there are many descriptions on liquefaction of subsoils. However, almost all of the descriptions before 1872 are rarely qualified from the viewpoint of engineering. Meanwhile, since 1872, liquefaction phenomena can be qualified in identifying liquefaction characteristics. In the descriptions, evidences of liquefaction in subsoil are given from i) water spouting with sand or mud from wells or cracks in the ground, ii) sand boils or sand volcanoes, iii) excessive settlements of heavy structures placed on sand layers and iv) floating out of wooden piles from rice paddy or floating out of caissons from river beds. However, the increase in water spouting in the area under the artesian condition was not adopted as an evidence of liquefaction of sands.

About 150 reports give information on liquefaction in 44 earthquakes listed in Table 1.

Table 1 Lists of earthquakes which induced liquefaction (1872-1968)

Earthquake	Date	Magnitude	Focal depth (km)	Epicenter	Persons killed
1. Hamada	1872.3.14	7.1		34.8°N, 132.0°E	552
2. Koshigun	1887.7.22	6.1		37.7°N, 139.0°E	0
3. Kumamoto	1889.7.28	6.3		32.8°N, 130.7°E	20
4. Nobi (Mino-Owari)	1891.10.28	8.4 (7.9)		35.6°N, 136.6°E	7,273
5. Tokyo	1894.6.20	7.5		35.7°N, 139.9°E	31
6. Shonai	1894.10.22	7.3		39.2°N, 139.5°E	726*
7. Tone-karyu	1895.1.18	7.3		35.9°N, 140.4°E	9
8. Rikuu	1896.8.31	7.5		39.5°N, 140.7°E	209
9. Kamitakai	1897.1.17,4.30	6.3, 6.3		36.6°N, 138.2°E	0
10. Minami Uonumagun	1898.5.26	6.7		36.9°N, 138.9°E	0
11. Fukuoka	1898.8.10,8.12	6.5, 6.5		33.5°N, 130.2°E	0
12. Gono (Anegawa)	1909.8.14	6.9		35.4°N, 136.3°E	41
13. Ugozen	1914.3.15	6.4		39.5°N, 140.4°E	94
14. Shimabara	1922.12.8	6.5, 5.9		32.7°N, 130.1°E	30
15. Kanto	1923.9.1	7.9		35.2°N, 139.3°E	99,331
16. Tajima	1925.5.23	7.0		35.7°N, 134.8°E	428
17. Kitatango	1927.3.7	7.5	10	35.6°N, 135.1°E	2,925
18. Ishinomaki	1927.8.6				
19. Sekihara	1927.10.27	5.3	0-10	37.5°N, 138.8°E	0
20. Kaga-nanseibu	1930.10.17				
21. Kita-izu	1930.11.26	7.0	0-5	35.1°N, 139.0°E	272
22. Nishi-Saitama	1931.9.21	7.0	10-20	36.1°N, 139.2°E	16
23. Noto	1933.9.21	6.0	15	37.1°N, 137.0°E	3
24. Shizuoka	1935.7.11	6.3	10	35.0°N, 138.4°E	9
25. Kawachiyamato	1936.2.21	6.4	20	34.5°N, 135.7°E	9
26. Kinkazan-oki	1936.11.3	7.7		38.2°N, 142.2°E	0
27. Oga	1939.5.1	7.0	0	39.95°N, 139.8°E	27
28. Nagano	1941.7.15	6.2	5-20	36.7°N, 138.3°E	5
29. Tottoriken-oki	1943.3.4, 3.5	6.1, 6.1	20,20	35.6°N, 134.2°E	0
30. Tottori	1943.9.10	7.4	10	35.5°N, 134.2°E	1,083
31. Tonankai	1944.12.7	8.0	0	33.7°N, 136.2°E	998
32. Mikawa	1945.1.13	7.1	0	34.7°N, 137.0°E	1,961
33. Nankai	1946.12.21	8.1	30	33.0°N, 135.6°E	1,330
34. Fukui	1948.6.28	7.3	20	36.1°N, 136.2°E	3,895
35. Tokachi-oki	1952.3.4	8.1	4.5	42.15°N, 143.85°E	28
36. Daishoji-oki	1952.3.7	6.8	20	36.45°N, 136.20°E	7
37. Tokushima-nanbu	1955.7.27			33.80°N, 134.30°E	1
38. Futatsui	1955.10.19	5.7	0-10	40.3°N, 140.2°E	0
39. Nagaoka	1961.2.2	5.2	20	37°27'N, 138°50'E	5
40. Hyuganada	1961.2.27	7.0	40	31°36'N, 131°51'E	2
41. Miyagiken-hokubu	1962.4.30	6.5	0	38°44'N, 141°08'E	3
42. Niigata	1964.6.16	7.5	40	38°21'N, 139°11'E	26
43. Ebino	1968.2.21,2.22/ 3.25	5.7, 6.1 5.6/5.7,5.4	0 0/0, 10	38°01'N, 130°43'E	3
44. Tokachi-oki	1968.5.16	7.9	0	40°44'N, 143°35'E	49

* in Yamagata Prefecture only

LIQUEFACTION DISTRIBUTION MAPS

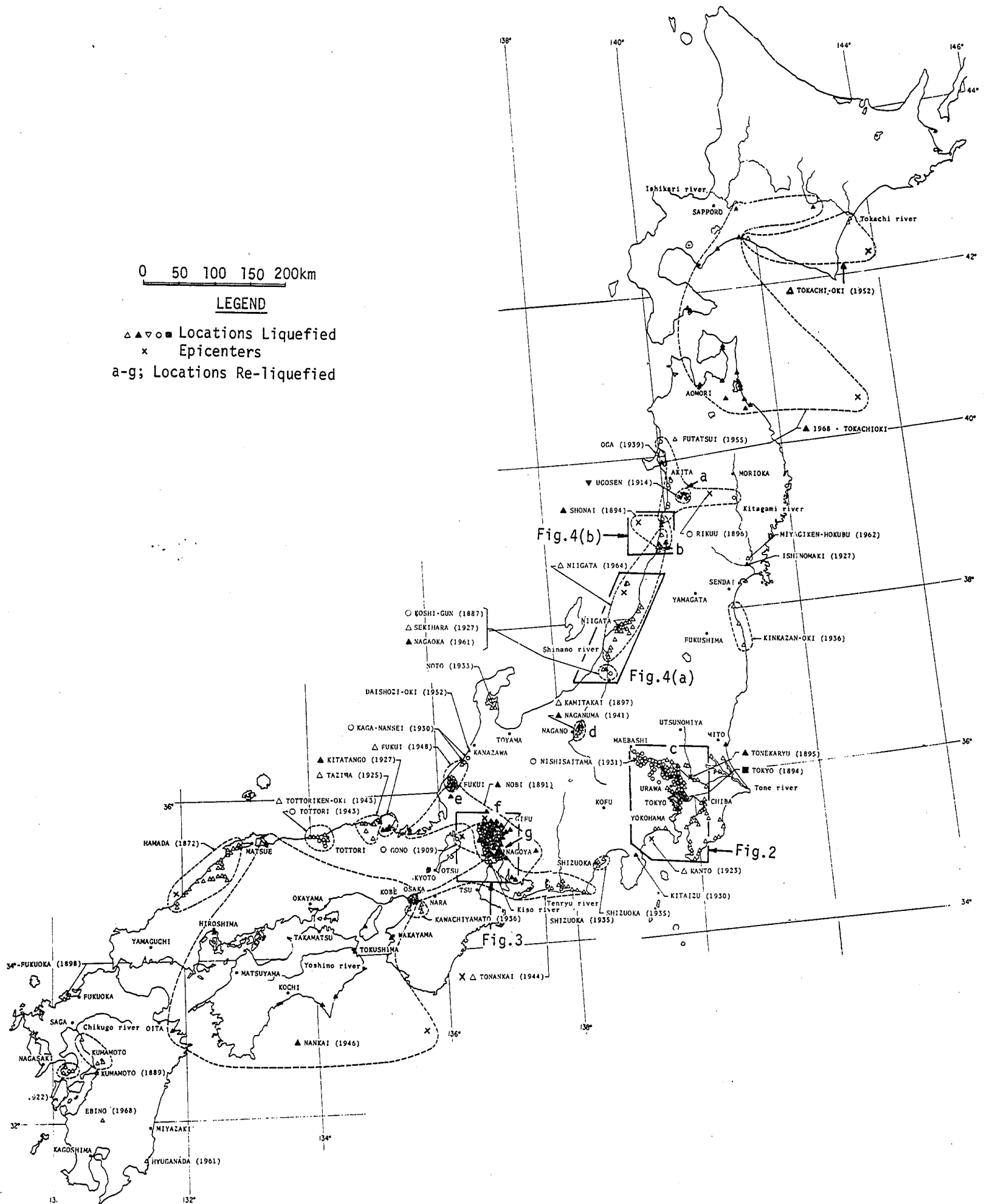
At least 44 earthquakes brought liquefaction of subsoils in Japan during the past century. Epicenters of the earthquakes and locations where liquefaction phenomena occurred are shown in Fig. 1. Characteristics of the earthquakes (date, magnitude, focal depth, epicentral location and fatalities) are listed in Table 1. Earthquakes with larger magnitude generally bring liquefaction in wider area, as shown in Fig. 1. Among the large earthquakes, the earthquakes No. 4 (Nobi), No. 12 (Gono), No. 15 (Kanto), No. 22 (Nishi-Saitama), No. 34 (Fukui) and No. 42 (Niigata) in Table 1 definitely brought widely spread and violent liquefaction in subsoils. Furthermore, the earthquakes No. 6 (Shonai), No. 8 (Rikuu), No. 16 (Tajima), No. 31 (Tonankai) and No. 44 (Tokachi-oki) brought locally violent spouting of water and made a number of large sand volcanoes. Maps of Kanto, Nobi and Hokuriku regions which give microscopic features of regions of densely distributed locations liquefied, are shown in Figs. 2, 3 and 4, respectively.

Kanto Region

Spouting of water containing dark blue or black fine sands from cracks in the ground were observed at many places in Kanto region during the earthquake No. 5 (Tokyo). In Fig. 2 the sites of liquefaction are denoted by solid circles with numbers 1 to 18 which are distributed only in alluvial areas close to the epicenter. With an interval of about 30 years from this earthquake, Kanto region was hit by the earthquake No. 15 (Kanto) which was one of the most disastrous earthquakes in the Japanese history. Sites of liquefaction during this earthquake are denoted by hollow triangles in Fig. 2 and are very widely spread in alluvial plains in Kanto region. It is noteworthy that many

Fig. 1 Liquefaction distribution map (Japan)

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liquefied sites are concentrated on the original winding river course of Tone river located to the northeast of Tokyo. About three hundred and fifty years ago, the estuary of the Tone river was linked to the Pacific Ocean by human power. The original Tone river used to flow into Tokyo Bay, and very deep and soft deposits with sand layers sedimented in the area of the old river course within a long period. Because of the revolution of the river course, higher potential of liquefaction has been retained in these sites in comparison with ordinary sites in Kanto plain. Both of the above earthquakes and also the earthquakes No. 7 and No. 22 (Nishi-Saitama) in this century brought liquefaction of subsoil in this area. Besides this area, sand boils, sand volcanoes and floating up of wooden piles and caissons during the earthquake No. 15 (Kanto) were reported as shown in Fig. 2 where representative liquefied sites are denoted by letters a, b, ..., K. For example, the site a is the reclaimed land in Kawasaki city where water with dark blue and grey fine sand ejected from dozens of cracks. At the site b near the epicenter, seven wooden piles floated up about 60 cm from a rice paddy during the quake (Photo. 1 and 2). These piles were used as bridge piles about 800 years ago over the original Sagami river. And at the site c many caissons for bridge foundations under construction floated up from the river bed of the Sagami river. (Photo. 3) More detailed description of liquefaction are reported in another paper (Kuri-bayashi, Tatsuoka and Yoshida, 1974).

The Earthquake No. 22 of 1931 (Nishi-Saitama) also induced liquefaction at many sites along the original and existing courses of Tone river. The liquefied sites during this earthquake are denoted by hollow circles in Fig. 2. One of the most violent water spouting was observed at the sites around Fukiage city about 20 km east of the epicenter where a large quantity of water with dark blue and grey fine sand ejected about 30 cm high and

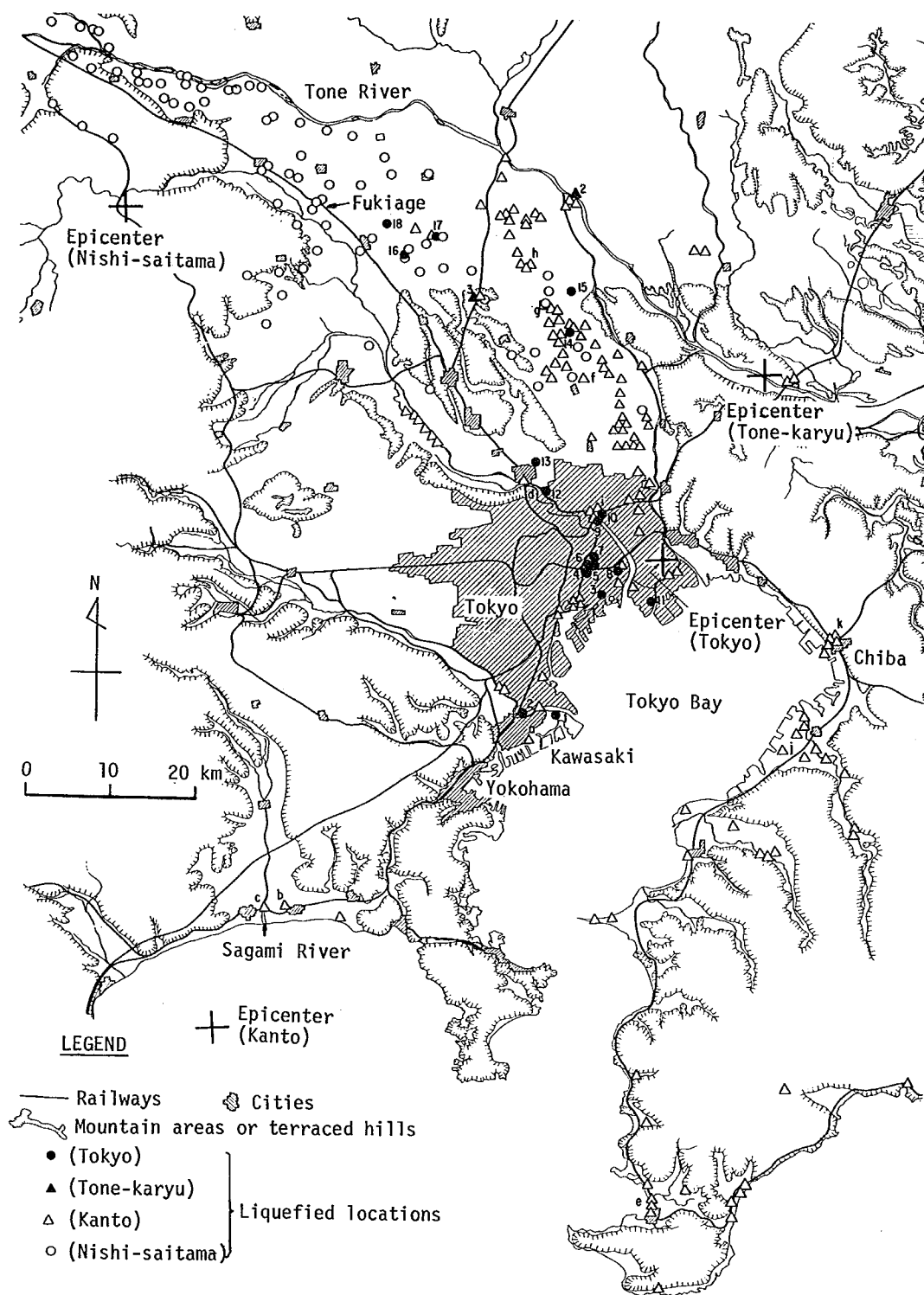


Fig. 2 Liquefaction distribution map (Kanto region)

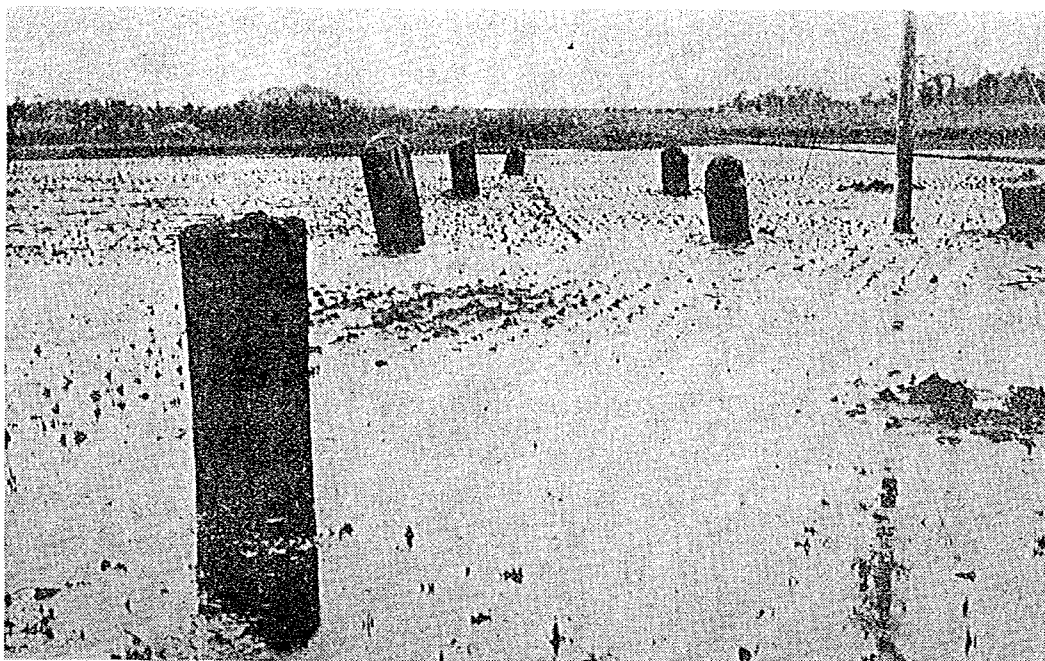


Photo. 1 A wooden pile which floated up from a rice paddy at Chigasaki during the Kanto Earthquake



Photo. 2 Wooden piles which floated up from a rice paddy at Chigasaki during the Kanto Earthquake

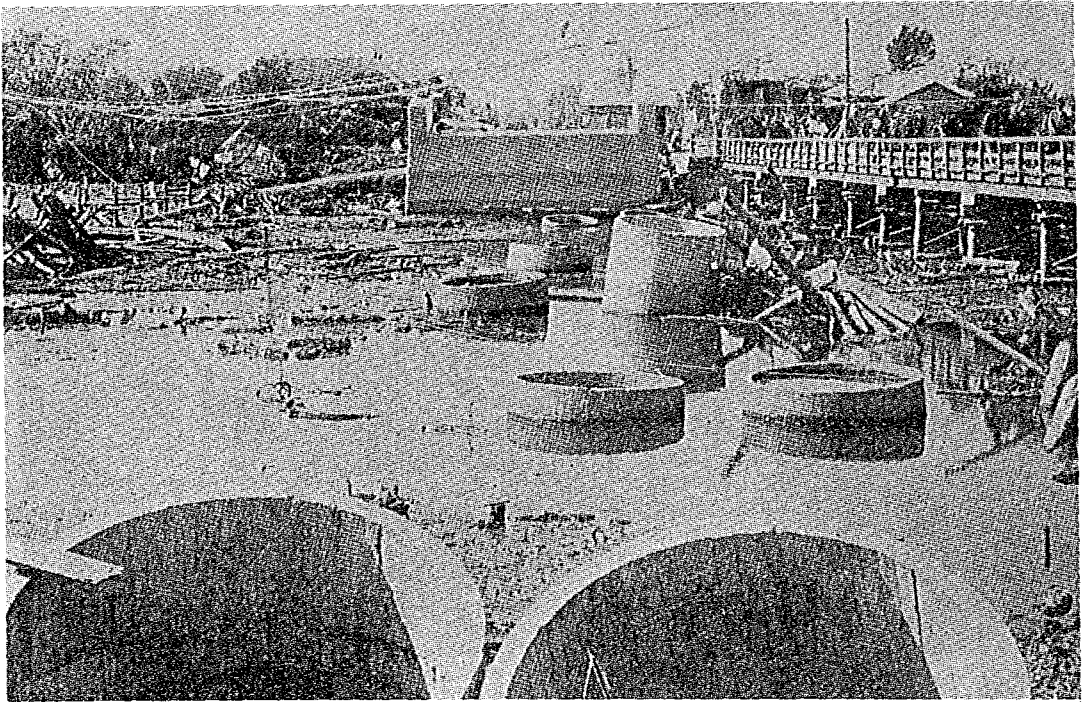


Photo. 3 Caissons under construction which floated up from the riverbed of the Sagami river during the Kanto Earthquake

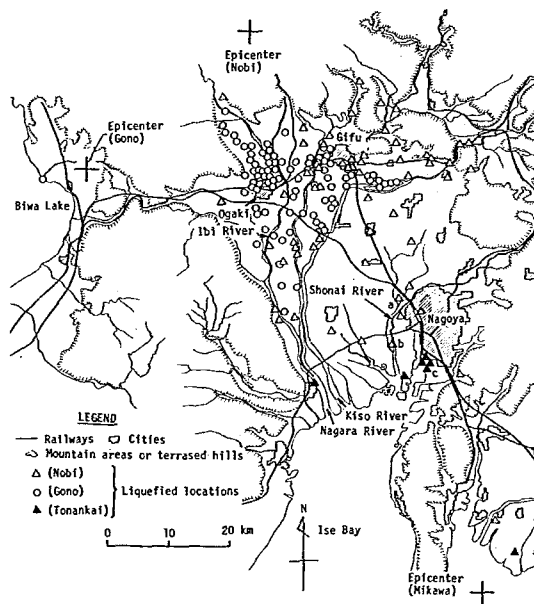


Fig. 3 Liquefaction distribution map (Nobi region)

several hundred sand volcanoes were observed. Furthermore, the ground surface of liquefied sites settled about 15 cm and spouted water covered the ground to a depth of about 15 cm.

Nobi (Mino-Owari) Region

The Nobi region has been inflicted by four violent earthquakes during the past century which induced liquefaction at many sites as shown in Fig. 3. Among them, the most violent one was the Earthquake No. 4 of 1891 (Nobi) which brought widely spread and violent liquefaction in Nobi plain and Fukui plain which are denoted by solid triangles in Fig. 1 and by hollow triangles in Fig. 3. Liquefied sites are limited to the alluvial soft deposits of the three rivers of Kiso, Nagara and Ibi in Nobi plain and to the sites along river courses in Fukui plain which is placed to the north of the epicenter. It would be noteworthy that the Earthquake No. 34 of 1948 (Fukui) also induced liquefaction in the whole of Fukui plain as shown in Fig. 1 (Photo. 4 and 5). The most violent water spouting during the Earthquake No. 4 was observed at the site denoted by the letter a in Fig. 3 near the Shonai river where water with sand ejected high above 2 m from wells and sands deposited over the roofs of nearby houses. And at the site b on the right bank of the Shonai river to the south of the site a, a thousand and several hundred sand boils were observed. The extent of liquefaction could be evaluated from the fact that rice paddy and field of about 40 km² in the prefectures of Aichi and Gifu were made impossible to be cultivated due to sand boils, necessitating repairs and reconstruction.

With an interval of eighteen years from this earthquake, the Earthquake No. 12 (Gono) brought liquefaction at many sites in the northwestern part of the Nobi plain where liquefaction had also been induced during the Earthquake No. 4. Many sites liquefied during this earthquake which are denoted by hollow

circles in Fig. 3. These were densely distributed in the area surrounded by three rivers of Ibi, Nagara and Kiso.

The Earthquake No. 31 (Tonankai) brought liquefaction in the coastal region with soft alluvial deposits between the Cape Omaezaki and Lake Hamana, and in the south coastal part of Nagoya city which had been reclaimed during the past hundred and fifty years prior to this Earthquake. Such liquefied sites are denoted by hollow triangles in Fig. 1 and solid triangles in Fig. 3. It was found that these liquefied sites were mostly distributed in severely damaged zones.

In the south coastal region of Nagoya city the damage to wooden houses such as settlement and tilting was mainly due to a very large quantity of ejected sand and water. Furthermore, many sand boils and water spoutings were observed at the sites of very severely damaged airplane factories at Nishi-inaei town which are denoted by the letter c in Fig. 3. It would be of interest that in the following Earthquake No. 32 (Mikawa) violent boiling of sand and water was observed again at the sites of these factories. Offshore earthquakes with large magnitudes such as the Earthquakes No. 31 (Tonankai), No. 33 (Nankai) and No. 44 (Tokachi-oki) have a character that most sites liquefied are located at the soft deposits in the coastal regions as shown in Fig. 1.

Hokuriku Region

Fig. 4 shows a liquefaction history of prefectures of Yamagata and Niigata during the past century. The Earthquake No. 6 (Shonai) brought liquefaction at many sites which are denoted by hollow triangles in Fig. 4(b). In Sakata city located at the rivermouth of the Mogami river, numerous sand boils were observed and the largest sand volcano reported was about 60 cm in height and about 3 m in diameter. The area where sands boiled most violently was covered by ejected sand and as a result this area looked like a

seashore. Similar violent sand boils were observed at the site 2 in Fig. 4 (b) where several tens of sand volcanoes were observed. The largest one was about 9 m in diameter. (Photo. 6 and 7). It is of interest that liquefaction occurred again in this site during the Earthquake No. 42 (Niigata) as shown in Fig. 4(b).

The earthquake No. 42 (Niigata) is well known for its widely spread liquefaction and the damage to modern buildings and civil engineering structures due to the liquefaction of deep saturated sand deposits. As this is reported in detail in many other reports, only a summary is presented in this paper. Liquefied zones during this earthquake are denoted by hatched zones with numerals 1 to 13 in Fig. 4 and it may be seen that these zones are limited to the original riverbeds of rivers of Shinano, Agano, etc. For example, the zone denoted by the letter a in Fig. 4(a) is the original riverbed of the Agano river which connected with Shinano river at the river mouth about three hundred year ago. (Photo. 8). This zone was reclaimed by sand about fifty years ago. The national highway No. 7 passes through this zone and its low bank made with sand of 1 m in height in this zone settled down about 1 m and moved laterally 4 m in the maximum during the earthquake. This would be due to liquefaction of sandy bank and sandy ground because boiled sand covered the road surface and one truck on the bank sank into the ground. (Photo. 9)

Furthermore, Photo 10 shows large holes in the liquefied ground at the zone No. 10 in Fig. 4 which is the old riverbed of Shinano river.

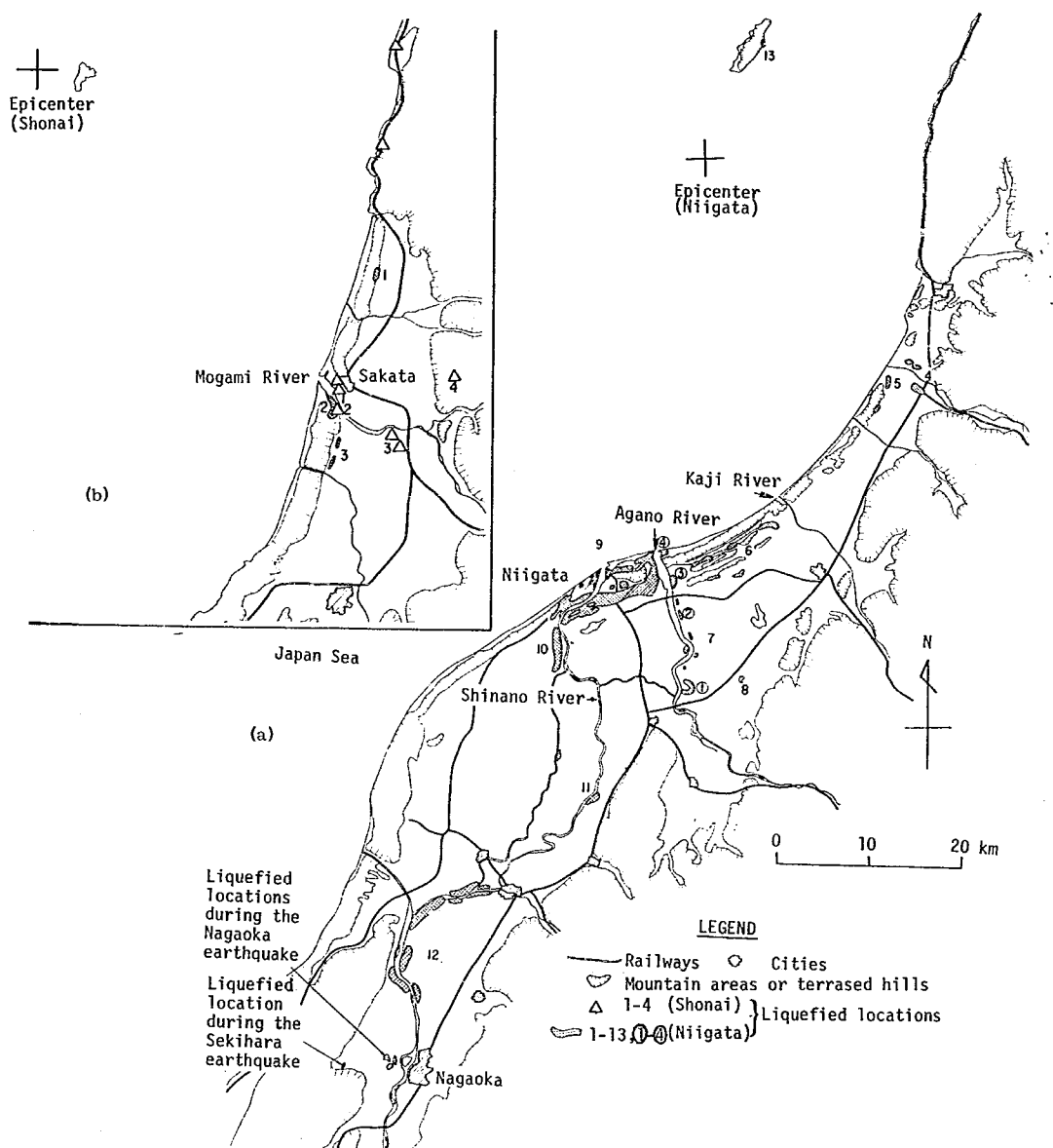


Fig. 4 Liquefaction distribution map (Hokuriku region)

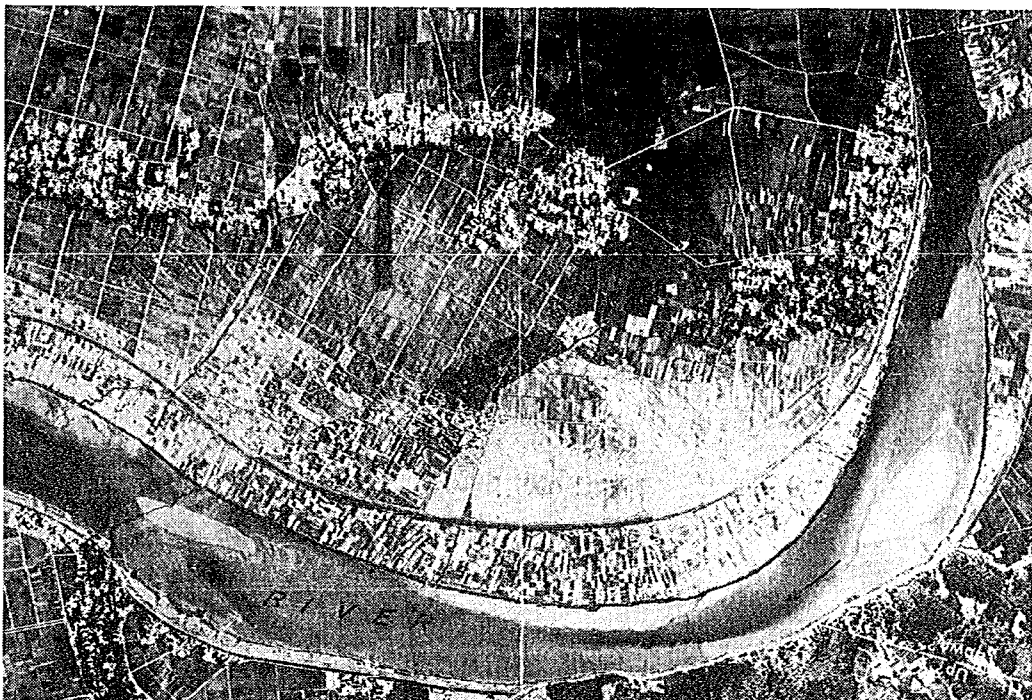


Photo. 4 Sand boils in rice paddies along Kuzuryu river in Fukui plain during the Fukui Earthquake

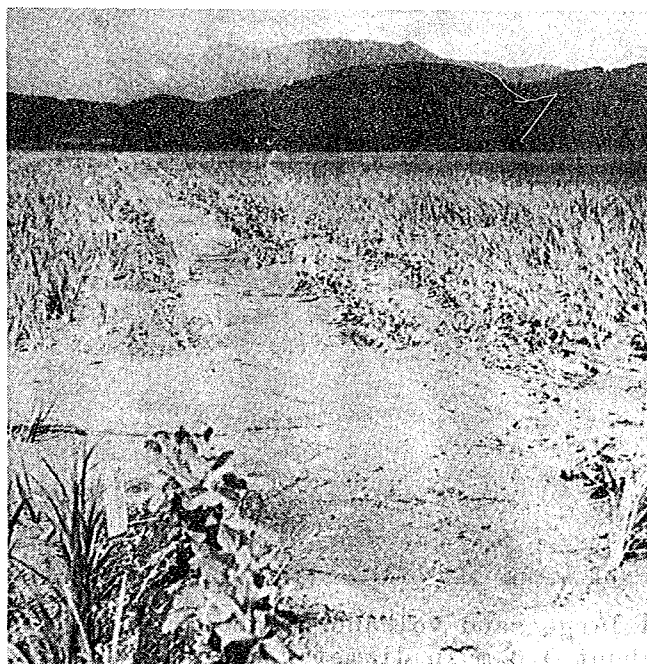


Photo. 5 Sand boils in rice paddies in the suburbs of Fukui city during the Fukui Earthquake

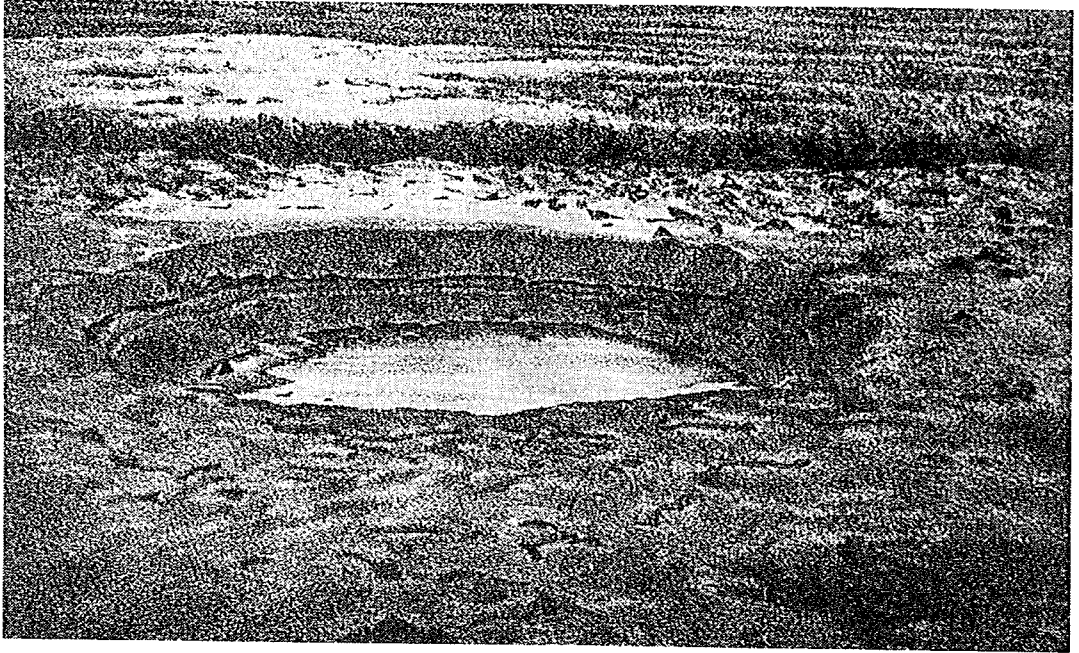


Photo. 6 A small pond of about 2.4 m in diameter made by water ejection near Mt. Iimori at the rivermouth of the Mogami river during the Shonai Earthquake

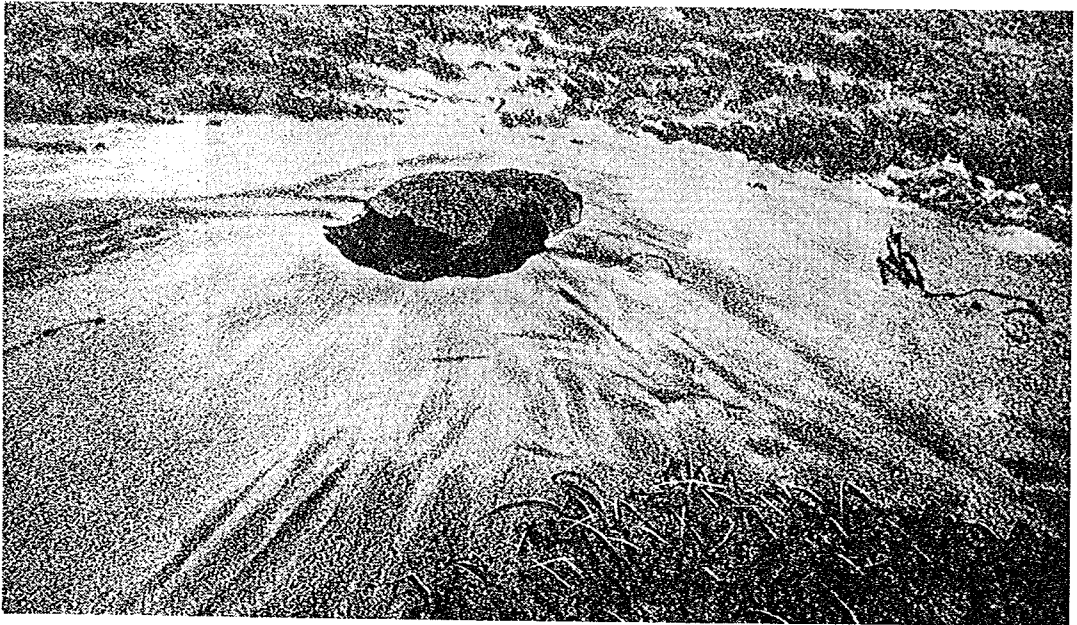


Photo. 7 A large sand volcano of about 30 cm in height and of about 3.6 m in diameter near Mt. Iimori made during the Shonai Earthquake



Photo. 8 Sand boils in the old riverbed of the Agano river
during the Niigata Earthquake



Photo. 9 A truck which sank into the liquefied low bank of the National Highway No. 7 at Ebigase during the Niigata Earthquake



Photo. 10 Large holes in the liquefied ground at the zone 10 in Fig. 4 which is the old riverbed of the Shinano river during the Niigata Earthquake

DISCUSSIONS AND REMARKS

From an extensive survey of liquefaction described in the above, the following was deduced.

(i) Re-liquefaction was observed in 7 zones at least as shown by the letters a to g in Fig. 1 and as listed in Table 2. This suggests that re-liquefaction occurs if certain conditions are satisfied.

(ii) One of the causes of liquefaction in subsoils is the intensity of ground motion. Earthquake intensity at liquefied site were estimated by comparing the both maps of liquefaction distribution and intensity scale distribution. From this procedure, it was found that estimated earthquake intensity on JMA (Japan Meteorological Agency) scale at liquefied sites were more than the fifth grade which means the maximum accelerations of 80 gals to 250 gals.

(iii) As well known, the liquefaction zone gets wider, the larger the earthquakes. In Fig. 5 the maximum epicentral distance of liquefied sites R (km) and the magnitude of the earthquake M are plotted. In relation with this arrangement Fukuoka (1971) suggested that this relationship could be expressed by

$$\log_{10} R = M - 5.7 \quad (1)$$

Eq. (1) is based on data of the earthquakes No. 33 (Nankai) and No. 42 (Niigata). Meanwhile it was found from Fig. 5 that the following equations express the linear relationship more appropriately than Eq. (1). The average line of the whole data in Fig. 5 is expressed by

$$\log_{10} R = 0.87M - 4.5 \quad (2)$$

and the lower bound for $M > 6.0$ is expressed by

$$\log_{10} R = 0.77M - 3.6 \quad (3)$$

Limiting discussions on the data of 44 earthquakes, a lower bound

of liquefaction in R-M relation can be conceivably anticipated by Eq. (3) and in Fig. 5. On the basis of this relation liquefaction may not occur at any site more distant than expressed by Eq. (3). For $M=7.0$, for example, liquefaction may not occur at more distant site than 60 km from epicenter.

Table 2. Zones where re-liquefaction was observed

a, b, ..., g correspond to those in Fig. 1.

Zones	Earthquakes
a: the narrow zone along the Omono River in the northwest of Oomagari city in Akita Prefecture	No. 8 (Rikuu) and No.13 (Ugosen)
b: on the left side at the river mouth of Mogami river	No. 6 (Shonai) and No.42 (Niigata)
c: in the original river course of Tone river on the northeast of Tokyo	No. 5 (Tokyo), No. 7 (Tonekaryu), No.15 (Kanto) and No.22 (Nishi-Saitama)
d: on the both sides of Chikuma river near Nagano city	No. 9 (Kamitakai) and No.28 (Nagano)
e: in the southern part of Fukui plain	No. 4 (Nobi) and No.24 (Fukui)
f: in the northwestern part of Nobi plain	No. 4 (Nobi) and No.12 (Gono)
g: in the southern part of Nobi plain	No.31 (Tonankai) and No.32 (Mikawa)

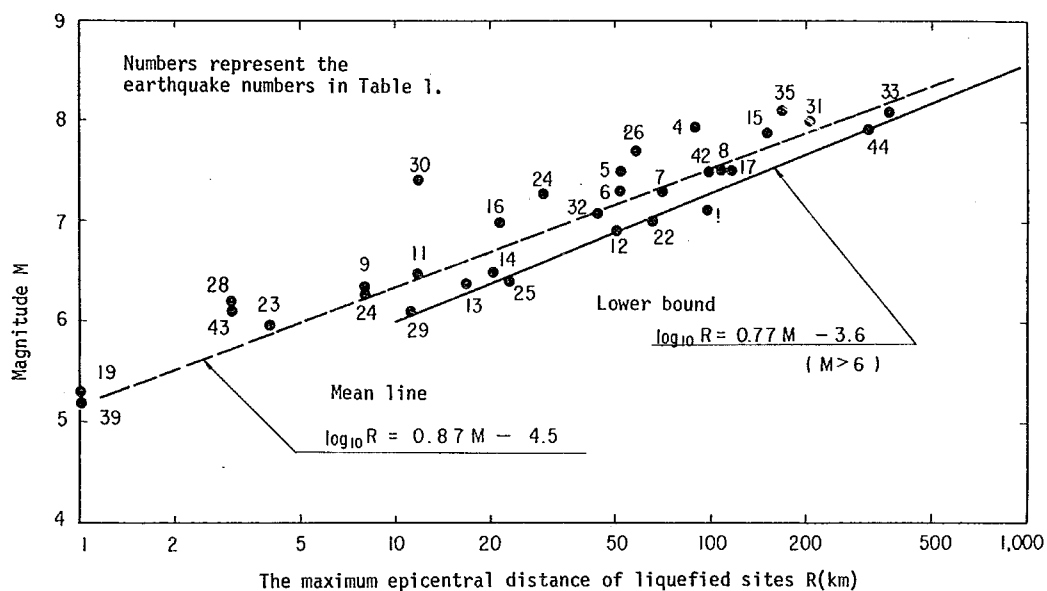


Fig. 5 Relationship between the maximum epicentral distance of liquefied sites R and magnitude M

CONCLUSIONS

By surveying many reports of earthquakes during the last century, it was found that liquefaction in subsoils was induced at many sites in Japan during at least 44 earthquakes and liquefied sites were limited only to alluvial deposits and reclaimed lands. Especially, liquefaction occurred selectedly in old river courses which had been reclaimed during the last few hundred years and in reclaimed lands along seas or lakes. Such tendency becomes clearer in case of offshore earthquakes with large magnitude. Furthermore, it could be inferred that liquefaction occurred repeatedly during different earthquakes in several zones while rigorous identification of liquefied sites is difficult. Estimated JMA intensity scale at liquefied sites were more than the fifth grade. A lower bound of liquefaction potential can be defined as a relation between epicentral distances and magnitude of earthquakes on the basis of this discussion.

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APPENDIX

Japan Meteorological Agency (JMA) Intensity Scale

0	No sensation: recorded by seismographs but no perception by the human body. { under 0.8 }
I	Slight: felt by persons at rest or persons especially sensitive to earthquakes. { 0.8 ~ 2.5 }
II	Weak: felt by most persons: slight rattling of doors and Japanese lattice paper sliding doors (shōji). { 2.5 ~ 8.0 }
III	Rather strong: shaking of houses and buildings; heavy rattling of doors and shōji, swinging of chandeliers and other hanging objects; movement of liquid in vessels. { 8.0 ~ 25.0 }
IV	Strong: strong shaking of houses and buildings; overturning of unstable objects; spilling of liquid out of vessels four-fifth full. { 25.0 ~ 80.0 }
V	Very strong: cracking of plaster walls; overturning of tombstones and stone lanterns; damage to masonry chimneys and mud-plastered warehouses. { 80.0 ~ 250.0 }
VI	Disastrous: demolition of Japanese wooden houses up to 30%; numerous landslides and embankment failures; fissures in flat grounds. { 250.0 ~ 400.0 }
VII	Ruinous: demolition of Japanese wooden houses more than 30%. { over 400.0 }

note) { } : Maximum acceleration, in gals

Magnitudes of Earthquakes

1. For earthquakes before 1922 in Table 1, the magnitude on the Kawazumi scale is defined as follows,

$$M_k = I + 0.00166(\Delta - 100) - 2 \log_e(100/\Delta) \quad (B-1)$$

where M_k is the magnitude on the Kawazumi scale, Δ is the epicentral distance in km and I is the intensities in JMA scale.

2. For earthquake, after 1923 in Table 1, the magnitude on the JMA scale is defined as follows,

$$M = \log_{10} A + 1.73 \log_{10} \Delta - 0.83 \quad (B-2)$$

where M is the magnitude, A is the maximum displacement recorded in cm and Δ is the epicentral distance in km.

P.W.R.I.M.C.

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- ・必ず期日を守りましょう。
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- ・折目をつけないようにしましょう。
- ・また貸しをやめましょう。