A HISTORY OF SOIL LIQUEFACTION IN JAPAN

by

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SYNOPSIS

In order to obtain the relationship between occurrence of liquefaction phenomena and site conditions involved, a literature survey on liquefaction occurred during earthquakes in the last century in Japan was made, and site conditions at liquefied site were investigated. It is found that liquefaction of subsoils was induced during at least 44 earthquakes since 1872. Liquefied sites were limited only to alluvial deposits and reclaimed lands along seas or lakes. Seismic intensity at the liquefied sites was estimated to be 5 or higher on the JMA scale.

INTRODUCTION

During the past major earthquakes many engineering structures were damaged due to liquefaction phenomena of saturated sandy deposits. Correlations between liquefaction and site conditions were investigated at several regions in Japan1), 2), 3), 4). Kuribayashi and Tatsuoka5), 6) performed a literature survey on liquefaction during 44 earthquakes in the last century throughout Japan. They obtained a distribution map for the whole Japan and regional precise maps for three areas, Kanto, Nobi, and Hokuriku. Furthermore detailed descriptions of liquefaction phenomena are provided. In these studies, liquefaction of subsoils is defined from the evidences such as 1) water spouting with sands and muds from wells or cracks on the ground, 2) sand boils or sand volcanoes, 3) excessive settlemente of heavy structures constructed in sand layers, and 4) floating of wooden piles from rice paddy and floating of caissons under construction from river beds. This paper will discuss factors affecting the occurrence of liquefaction of soils, on the basis of the studies of the experienced history in Japan.

FACTORS AFFECTING LIQUEFACTION OCCURRENCE

Fig. 1 shows a relationship between magnitudes (M) of earthquakes and distances (R) from the epicenters to the most distant liquefied points. Numerals in the figure represent the earthquakes listed in Table 1 where earthquake names, dates, magnitudes, focal depths, epicenters, and number of victims are presented. All of these earthquakes induced liquefaction in certain areas. It is noted from Fig. 1 that the liquefaction area becomes wider as the magnitude of earthquake gets higher. From Fig. 1 an average relation between M and R can be expressed by

$$\log_{10} R = 0.87\, M - 4.5 \quad (R\ ;\ \mathrm{km}) \qquad (1)$$

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and the lower bound is approximately expressed by

$$\log_{10}R = 0.77\,M - 3.6 \quad (R\ ;\ \mathrm{km}) \qquad (2)$$

for earthquakes with magnitudes larger than 6.0. It is suggested that liquefaction may occur only inside an area with redius of R given by eq. (2). For example, for M = 6, 7, and 8 the values of R are 10, 60 and 360 km, respectively.

One of factors affecting liquefaction may be the intensity of ground shaking. An area of highly intense ground motion will become wider for a larger earthquake. Therefore, the area where liquefaction occurred gets wider for a larger earthquake. It was found that seismic intensity on the JMA (Japan Meteorological Agency) scale was 5 or higher at liquefied sites, which corresponds to the maximum acceleration at the ground surface of 80 to 250 gals or higher.

In Fig. 2 shown are the equi-average maximum ground acceleration lines presented by the Public Works Research Institute7) through the results of strong-motion observation for earthquakes which occurred in or near Japan. The average maximum acceleration (equal to 100 gals at base rock) obtained through the observation in the western part of the United States8) is also indicated by a dotted line. Also shown in this figure is the lower bound line with points which represent the relationship between the magnitude (M) and the maximum epicentral distance of liquefied sites (R). It is noted that the slope of the lower bound line for liquefaction does not coincide with these of the equi-average maximum acceleration lines, and that along the lower bound line the average maximum acceleration becomes smaller for the larger earthquakes. On the other hand, the duration of the strong ground motion becomes longer for larger earthquakes and the predominant period of the ground motion becomes longer at distant sites from epicenters. It is inferred that the duration and the predominant period of ground motion shall be considered in assessing liquefaction potential as well as the maximum acceleration.

Another factor affecting liquefaction might be ground conditions. Fig. 3 shows the relationship between the locations of liquefied sites, old and present riverbeds and soil conditions in the eastern part of Saitama Prefecture located north of Tokyo. This shows clearly that liquefaction occurred only in the alluvial deposit and densely in or along the old and present riverbeds. Boring logs and soil profiles at the representative liquefied zones are shown in Fig. 4 and Fig. 5, respectively. Hollow circles, hollow triangles and a solid circle in Fig. 5 represent liquefied sites and correspond to the marks in Fig. 3. From these figures, the followings can be found. First, the ground water levels are high at all of these liquefied sites. Furthermore, in the alluvial fan of Tone river, the representative section A-A' of which is shown in Fig. 5, liquefaction occurred in the alluvial sand layer (As) and in the alluvial sandy gravel layer (Ag). N-values (number of blows by the standard penetration test) of the sandy gravel layer are large as shown in Fig. 4. However, high N-values would be due to gravels and would not indicate the high density of the layer. In the middle reach of rivers where sandy banks are naturally formed liquefaction occurred in the upper alluvial sand layer

(As-1). The representative section B-B' is presented in Fig. 5. As shown in Fig. 4, N-values of this layer are about 10 to 20 which correspond to the medium density. In the delta of rivers, the representative profile C-C' of which is shown in Fig. 5, liquefaction occurred also in the upper alluvial sand layer (As-1). The density of soils in the delta is relatively loose with the N-values of about 2 to 10.

CONCLUSIONS

By surveying the relation between liquefaction phenomena and site conditions in Japan in this century, the followings are found.

1) A lower bound for liquefaction potential can be defined as a relation between epicentral distances and magnitudes of earthquakes.
2) To evaluate liquefaction potential, duration and predominant period of ground motion as well as maximum acceleration should be taken into account.
3) Liquefaction occurred exclusively at alluvial sandy deposits and reclaimed lands, especially severely at reclaimed lands where rivers, seas or lakes existed in the near past.

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REFERENCES

1) Miyabe, N. (1933) : "On the abnormality of ground water during earthquakes," Earthquakes, Vol. 5 (in Japanese).
2) Kishida, H. (1969) : "Characteristics of liquefied sands during Mino-Owari, Tohnankai and Fukui earthquakes," Soils and Foundations, Vol. IX, No. 1.
3) Iida, K. (1974) : "Past earthquakes and damage in Nagoya city," Report of Committee for Disaster Prevention of Nagoya city (in Japanese).
4) Ishihara, K. (1974) : "Liquefaction of subsurface soils during earthquakes," Technocrat, Vol. 7, No. 5.
5) Kuribayashi, E., Tatsuoka, F. and Yoshida, S. (1974) : "Liquefaction history in Japan during the last century," Bull. of Public Works Research Institute, No. 30 (in Japanese).
6) Kuribayashi, E. and Tatsuoka, F. (1975) : "Brief review of liquefaction during earthquakes in Japan," Soils and Foundations, Vol. 15, No. 4, Dec.
7) Kuribayashi, E. and Iwasaki, T. (1972) : "A Report on the activity of earthquakes around the bay of Tokyo," Report of Public Works Research Institute, No. 745.
8) Schnabel, P. B. and Seed, H. B. (1972) : "Accelerations in rock for earthquakes in the western United States," EERC 72-2, Earthquake Engineering Research Center, University of California.

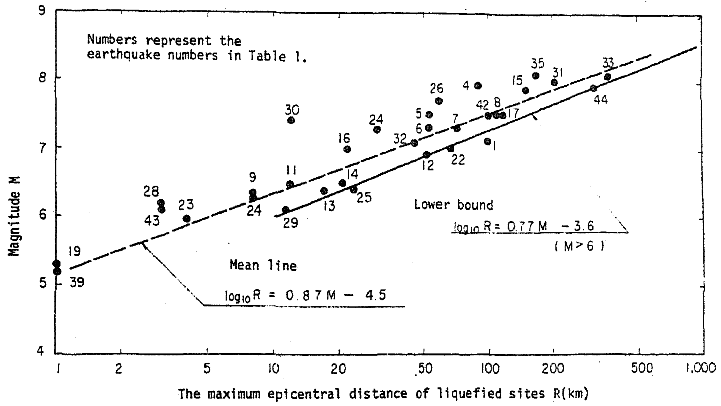

Fig. 1 Relationship between the maximum epicentrical distance of liquefied sites R and magnitude M5)

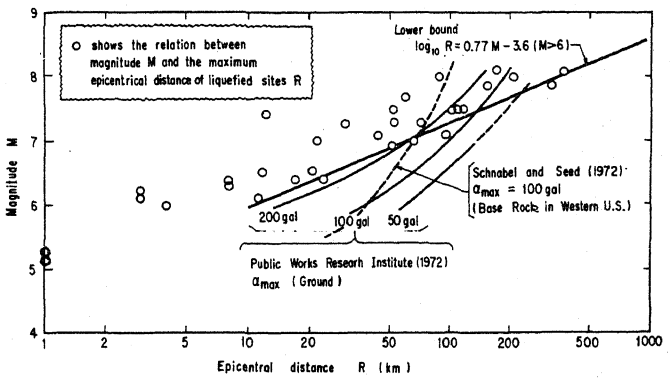

Fig. 2 Average maximum acceleration at the liquefied sites

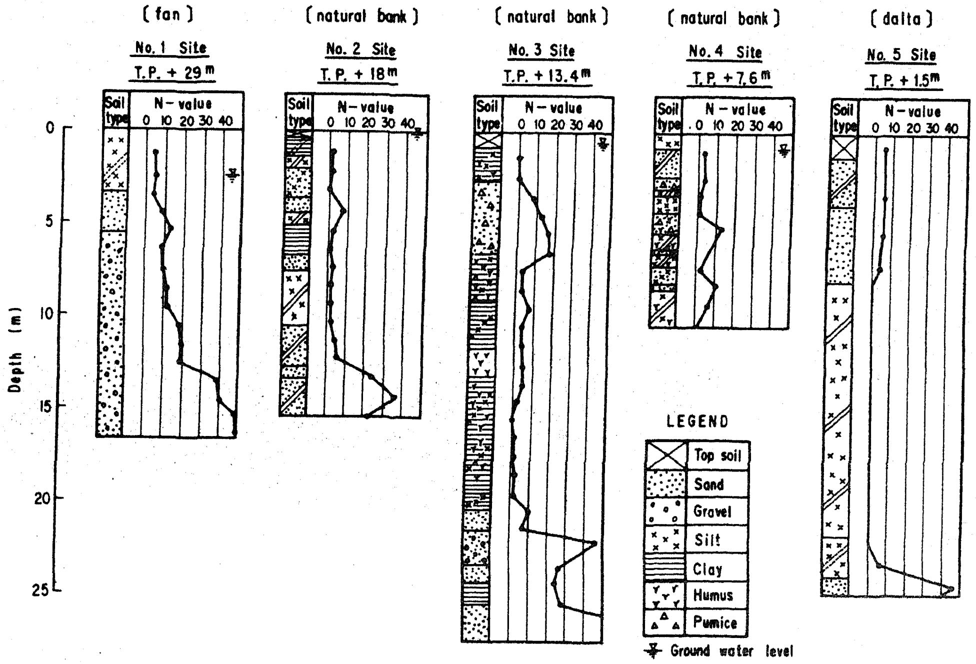

Fig. 4 Boring logs at the representative liquefied sites (See Fig. 3)

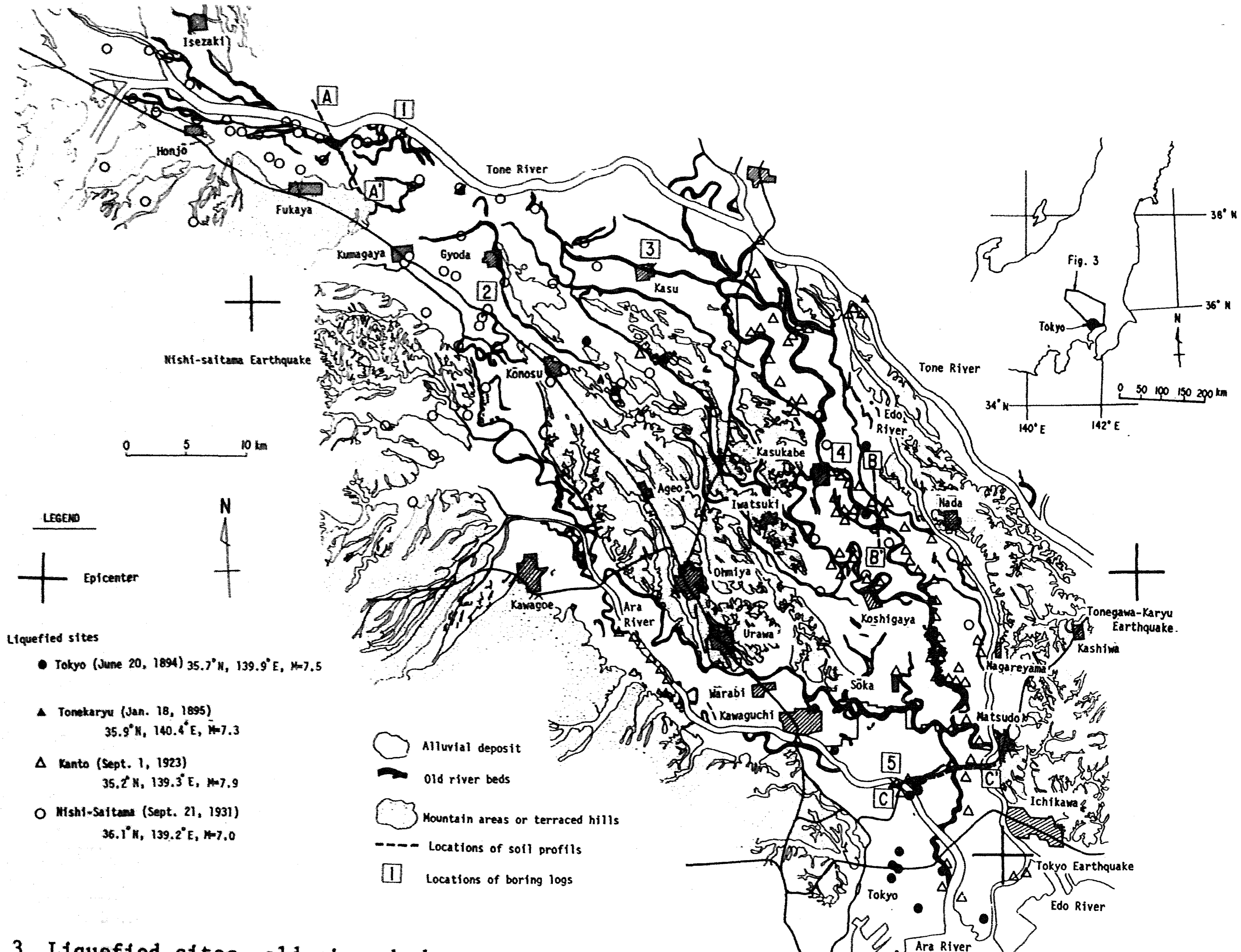

Fig. 3 Liquefied sites, old river beds and soil condition in the eastern Saitama Prefecture

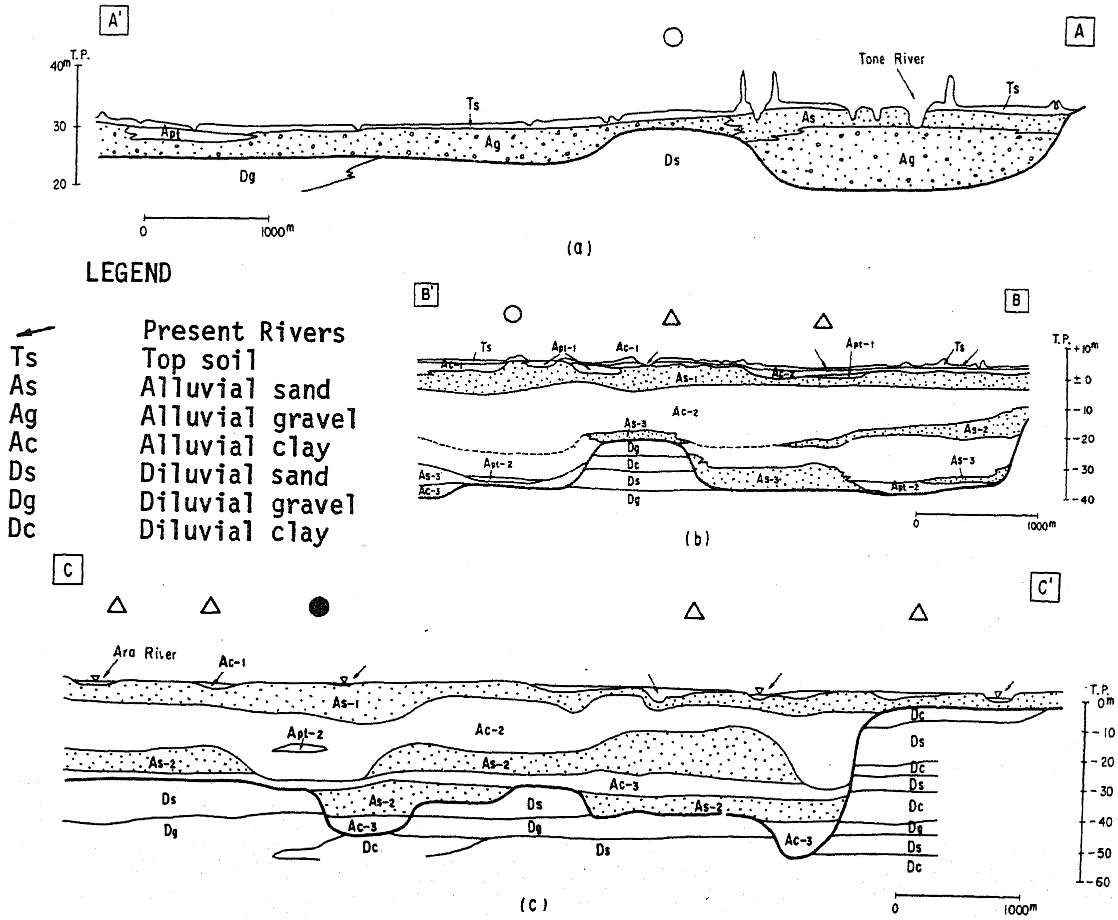

Fig. 5 Soil profils of liquefied zones (See Fig. 3)

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

	Earthquake	Year, Month, 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.	Ugosen	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

DISCUSSION

H.N. Gandhi (India)

What is the depth of water table in most of the cases in case of liquefaction in Japan. Also the author may indicate whether liquefaction occured only in pure sandy soil or whether liquefaction was observed in sandy clayey strata. In the later case what was the percentage of clay content and other physical properties of such soils.

Author's Closure

With regard to the question of Mr. Gandhi, we wish to state that;

(1) According to our survey, the most cases of liquefaction took place in the area where the depth of ground water table is rather shallow in the case of Japan. While detailed values about ground water table can not be indentified for all the cases, it may be deduced that the average depth of ground water table is around 0 to -3m in the area where liquefaction occured.

(2) Pure sands without fine soils are rarely found in actual sandy deposits. Also in relating to soil liquefaction, it has been observed that liquefaction occurred even in silty sand deposits or in sandy silt deposits which are developed besides rivers. For example, in the case of liquefaction observed in a reclaimed land during the 1968 Tokachi-oki Earthquake, some sand volcanoes of sandy silt were found. D_{20} and D_{60} of the sandy silt were around 0.01mm and 0.04mm, respectively. On the basis of these experiences, an article of "Sandy Soil Layers Vulnerable to Liquefaction", in the specifications for Earthquake Resistant Design of Highway Bridges (Japan Road Association - 1971) reads as follows.

Saturated sandy soil layers which are within 10 meters below the actual ground surface, have a standard penetration test N-value less than 10, have a coefficient of uniformity less than 6, and also a D_{20}-value of the grain size accumulation curve between 0.04 mm and 0.5 mm, shall have a high potential for liquefaction during earthquakes. Bearing capacities of these layers shall be neglected in design.

Saturated sandy soil layers which have a D_{20}-value between 0.004 and 0.04 mm or between 0.5 and 1.5 mm may liquefy during earthquakes, and shall be given an attention. Estimation in the case shall be made in accordance with the available information on liquefaction problems.

When a special investigation is performed, the above article may bot be required to apply.