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LIQUEFACTION OF THE GROUND DURING THE 1978 MIYAGIKEN-OKI EARTHQUAKE

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ABSTRACT

Immediately after the Miyagiken-Oki earthquake of June 12, 1978, the authors found 38 liquefaction sites. At most of these sites, settlement of river dikes, uplift of sewage tanks, tilting of quay walls and other damage were caused by liquefaction. At some liquefaction sites, no structural damages were observed. The degree of liquefaction at each liquefaction site, the ground conditions, the relation between liquefaction and resultant damage, and the characteristics of liquefied sand are discussed in this paper. Sedimentary environments of boiled sands are inferred by grain size distributions at nine liquefaction sites. Moreover depths of liquefied layers at two sites are estimated based on the correlation between the grain size distribution of boiled sand and that of soil samples.

Key words: case history, earthquake, earthquake damage, grain size, liquefaction, sandy soils, site investigation, sedimentary deposits

IGC: C 9/B 4/E 8

INTRODUCTION

On June 12, 1978, the north-eastern part of Japan was shaken by a strong earthquake of magnitude 7.4. This earthquake was named the 1978 Miyagiken-Oki earthquake by Japan Meteorological Agency. At many locations in the area from the Abukuma River basin to the Kitakami River basin, sand liquefactions were induced by this earthquake. Sand liquefaction occurred in recent reclaimed fills and floodplains of rivers, along river banks, in old river beds and on beaches. Liquefaction caused ground subsidence, failure of embankments and retaining walls, settlement of buildings, and floatation of buried sewage treatment tanks. However, several structures were not damaged in spite of liquefaction around the sites because of their firm foundations which had been properly constructed. Distributions of the sites of liquefaction, the characteristics of liquefied sands and the features of damages during the Miyagiken-Oki earthquake will be described. Liquefaction sites will be classified into three groups according to the relation between liquefaction and the resultant damage. The environment of the liquefied sands during sedimentation will be inferred from the grain size frequency distribution of each sand.

MIYAGIKEN-OKI EARTHQUAKE

At 5:14 p.m. on June 12, 1978 (Japan Standard Time), a fairly strong earthquake hit

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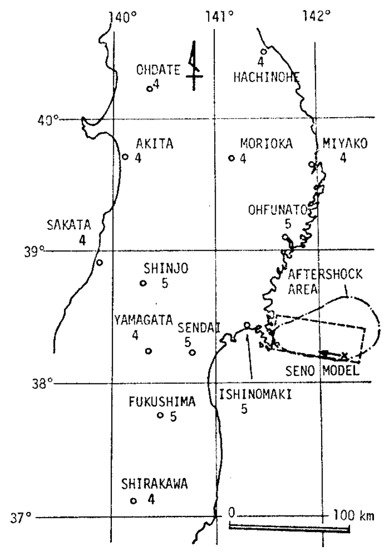


Fig. 1 Seismic intensity map (Miyagiken-Oki earthquake by JMA)

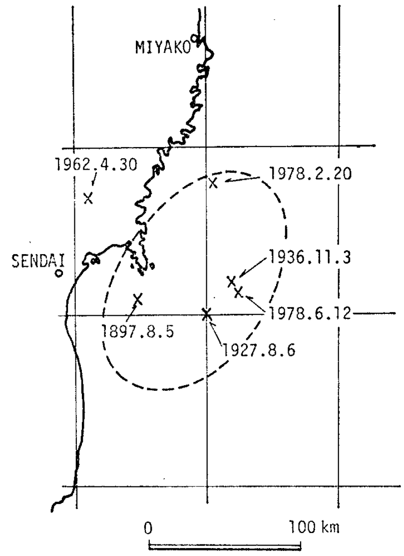


Fig. 2 Seismic source zone and epicenters

the north-eastern part of Japan. The Japan Meteorological Agency (JMA) named this earthquake the 1978 Miyagiken-Oki earthquake. This earthquake of magnitude 7.4 occurred about 100 km east of Sendai City. The epicenter was located at 142°13′E and 38°09′N by JMA and the focal depth was estimated at 30 km below sea level. The length and width of the fault plane were estimated by Seno et al. (1978) to be 30 km and 80 km, respectively, as shown in Fig. 1. The JMA intensity scale of V was recorded in Sendai, Ishinomaki, Ohfunato, Fukushima and Shinjo, Fig. 1. An area encircled by chain curves in this figure corresponds to the aftershock area obtained from Utsu's formula (Utsu and Seki, 1955).

An area encircled by broken lines and points shown by crosses in Fig. 2 indicate the seismic source zone and the epicenters in this area, respectively. Prior to the Miyagiken-Oki earthquake, an earthquake of magnitude 6.7 (M=6.7) occurred on February 20, 1978, as shown in Fig. 2. Many large earthquakes have occurred in the source area of Miyagiken-Oki. Two strong earthquakes occurred for the last hundred years. One occurred in 1897 (M=7.3) and the other in 1936 (M=7.7).

The 1978 Miyagiken-Oki earthquake caused extensive damages to numerous structures such as bridges, buildings, river dikes, port facilities, etc. (Kobayashi et al., 1978; Hoshihata, 1978; Building Research Institute, 1979; Tsuchida et al., 1979). About 1 000 persons were injured and 28 persons were killed. Total damage was estimated at about 172 billion yen.

DISTRIBUTION OF LIQUEFACTION SITES

Liquefaction sites are indicated in Fig. 3. Table 1 describes the liquefaction and damage at each site. The liquefaction sites were recognized by miniature sand volcanoes which had been formed by eruptions of water and sand soon after the earthquake.

Kuribayashi and Tatsuoka (1975) reviewed liquefaction sites of the past 44 earthquakes and derived the following formula between the maximum epicentral distance of liquefied sites R(km) and the magnitude of an earthquake M:

$$\log_{10} R = 0.77M - 3.6 \qquad (1)$$

Substituting 7.4 for M into the above equation, the maximum epicentral distance of

Table 1. Liquefaction and damage at each site during the Miyagiken-Oki earthquake

Location: City or town	Location: District	Liquefaction site	Location of sand volcanoes	Damage due to the erthquake	Site No.
Watari Town	Torinoumi	Dike along the Torinoumi Inlet	Inside base of the dike and adjacent field	Settlement of the dike 1.6 m and swell of the inlet wall	A- 1
		Building lots	Bases of retaining walls and ground surface	Swell and collapse of the retaining walls and subsidence of the ground	A- 2
		Dike along the Torinoumi Inlet	Inside base of the dike and adjacent field	Swell and settlement of the inlet walls	A- 3
	Arahama	National recreation center	Around a sewage tank	Uplift of the sewage tank	A- 4
		Swimming pool in Torinoumi Park	Bottom of the swimming pool	Bent of the bottom of the swimming pool	A- 5
		Athletic field in Torinoumi Park	Ground surface and bases of the retaining walls	Tilt of th retaining walls	A- 6
		Baseball park in Torinoumi Park	Ground suface	Tilt of a public lavatory	A- 7
		Residential area	Field	Tilt and settlement of houses	A- 8
		Arahama sewage plant	Base of gravel fill	Subsidence of the surrounding ground	A- 9
		Farm	Field	Damage to crops	A-10
		Dike of the Abukuma River	Outside base of the dike and adjacent sand bar	Cracks of the surface of the dike	A-11
	Tazawa	Abukuma Bridge of the Johban Line	River bed	None	B
Iwanuma City	Niihama	Dike of the Abukuma River	Outside base of the dike	Cracks on the surface of the dike	C
Natori City	Yuriage	Yuriage-Ohashi Bridge	River bed	Cracks at the piers	D
	Nakata	Natori Bridge	River bed	None	E
	Yuriage-kami	Dike of Natori River	Both sides of the base of the dike	Cracks on the surface of the dike	F- 1
Sendai City	Nakamura	Dike of Natori River	Both sides of the base of the dike	Collapse of the dike	F- 2
Matsushima Town	Takagi	Near Takagi River	Around a pumping house	Tilt of the pumping house and floatation of a sewage tank	G- 1
	Tedaru	Farm	Field	Damage to crops	G- 2
Naruse Town	Suzakihama	Beach	Backshore	None	H
Yamoto Town	Ohmagari-hama	Sports field	Ground surface	Subsidence of the ground 50 cm	I- 1
		Sea bank	Inside of the bank (old backshore)	Movement of the sea bank	I- 2
	Ohmagari	Canal embankment	Inside base of the embankment	Settlement of the embankment 1 m	I- 3
		Canal embankment	Inside base of the embankment	Settlement of the embankment and damage to crops	I- 4
Ishinomaki City	Kohyo	Kohyo Elementary School	School yard	Floatation of a sewage tank	J- 1
		Residential area	Floor of houses and adjacent roads	Slight uplift and nonuniform subsidence of houses	J- 2
	Ishinomaki Port	Quay	Aprons and adjacent roads	Tilt of quay walls	K- 1
	Ishinomaki Fishing P.	Quay	Aprons and adjacent roads	Tilt of quay walls	K- 2
Kahoku Town	Yokote	Mouth of Kitakami River	Sand bar	—	L
	Magaki	Dike of Kitakami River	Inside base of the dike	Cracks on the surface of the dike	M- 1
		Dike of Kitakami River	Inside base of the dike and adjacent field	Cracks on the surfase of the dike and damage to crops	M- 2
	Kawamae	Dike of Kitakami River	Both sides of the base of the dike	None	N
Kanan Town	Oiri	Dike of Old Kitakami River (19.2 km)	Both sides of the base of the dike & adjacent field	Cracks on the surface of the dike	O- 1
		Dike of Old Kitakami River (19.9 km)	Both sides of the base of the dike & adjacent field	Cracks on the surface of the dike	O- 2
	Kitawabuchi	Dike of Eai River	Old river bed	Cracks on the surface of the dike	P
Ohsato Town	Higashizawa	Dike of Yoshida River	Both sides of the base of the dike	Settlement of the dike 50 cm	Q- 1
	Fukuro	Dike of Yoshida River	River bed	Cracks on the surface of the dike	Q- 2
Rifu Town	Shinyachi-waki	Base of the New Tohoku Railway	Around the footings	None	R

Table 2. Earthquake produced liquefaction in Miyagi prefecture before the Miyagiken-Oki earthquake

Name	Date	Magnitude	Liquefaction Sites
Ishinomaki	1927. 8. 6	6.9	Wakuya Town
Kinkazan-Oki	1936. 11. 3	7.7	Odaka Town, Isobe, Arahama (Site A in Table 1)
Miyagiken-Hokubu	1962. 4. 30	6.5	Ohbukuro, Noyachi
Miyagiken-Oki	1978. 2. 20	6.7	Nakamura (Same as Site F-2 in Table 1)

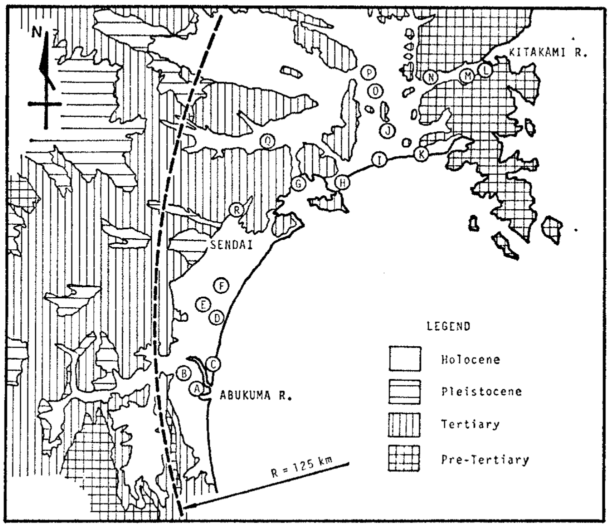


Fig. 3. Liquefaction distribution map by the Miyagiken-Oki earthquake

liquefiable sites due to the Miyagiken-Oki earthquake is estimated to be 125 km from the epicenter. The estimated maximum epicentral distance is shown by a broken curve in Fig. 3. It can be seen in this figure that all the liquefied sites located within this boundary.

As listed in Table 2, several earthquakes produced liquefaction in Miyagi Prefecture before the Miyagiken-Oki earthquake. Comparing Table 1 with Table 2, it seems that liquefaction reoccurred at two sites, Arahama and Nakamura, during the Miyagiken-Oki earthquake.

DESCRIPTION OF EACH LIQUEFACTION SITE

Liquefaction Sites Where Earth Structures were Damaged

As shown in Photo. 1, a retaining wall at a dike along Torinoumi Inlet (Site A-1, shown in Fig. 1 and Table 1) moved slightly toward the inlet and the surface of the backfill of the dike settled about 1.6 m. This large settlement appears to have been caused by liquefaction, because the volume of the settled dike was far greater than that due to the tilting of the wall, and sand volcanoes were found at the inside base of the dike and adjacent field. The fill material of the dike might have flowed into the Torinoumi Inlet.

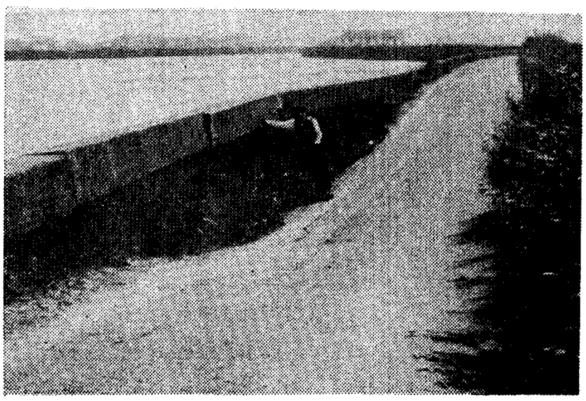


Photo. 1. Damage at a dike along Torinoumi Inlet (Site A-1)

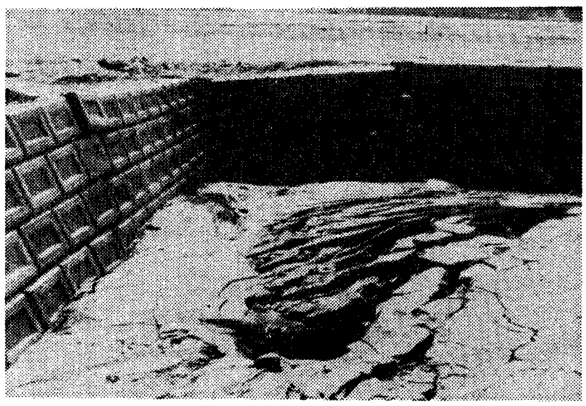


Photo. 2. Bulged and collapsed retaining wall at a residential quarter (Site A-2)

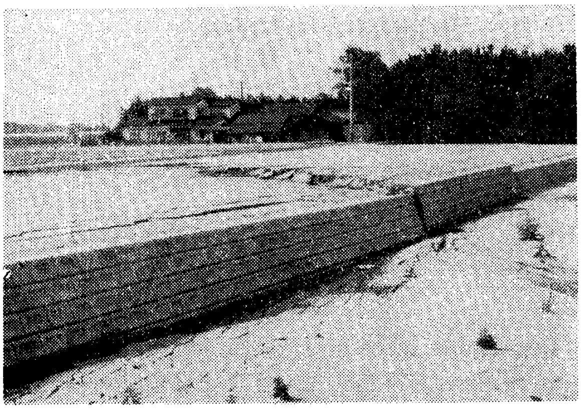


Photo. 3. Cracked and subsided ground at a recently filled residential quarter (Site A-2)

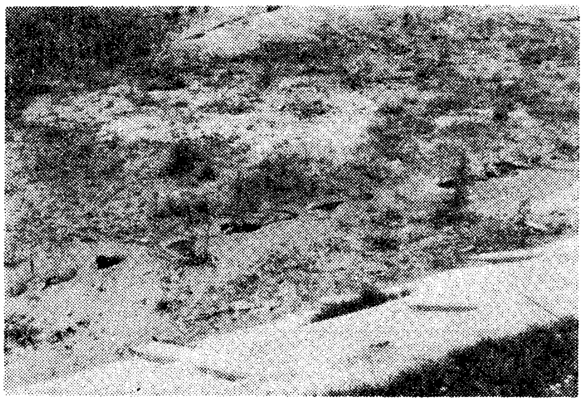


Photo. 4. Sand volcanoes from outside base of river dike (Site A-11)

At a recently filled residential area (Site A-2), liquefied sands, cracks and subsidence of ground surface, and bulged and collapsed retaining walls were observed (see Photos. 2 and 3). Fortunately, no house had been built yet.

At the mouth of Abukuma River (Sites A-11 and C), sand volcanoes were observed only 2 m from the outside base of the river dike, parallel to the longitudinal direction of the dike, as shown in Photos. 4 and 5, and the surface of the dike was wavy and cracked. The grain size distribution curves of these liquefied sands are shown in Fig. 14.

The river embankment was partially collapsed and cracked on both sides at Yuriage-kami (Site F-1) and at Nakamura (Site F-2) located about 3 km upstream from the mouth of Natori River. Sand volcanoes were observed at the both sides of the base. It is interesting to note that boiled sand had also spewed out at the inside base of the embankment at Nakamura by another earthquake on February 20 of the same year. This embankment was damaged by a flood in 1950. Fig. 4 shows the representative soil profile at this site (Iwasaki and Tokida, 1980).

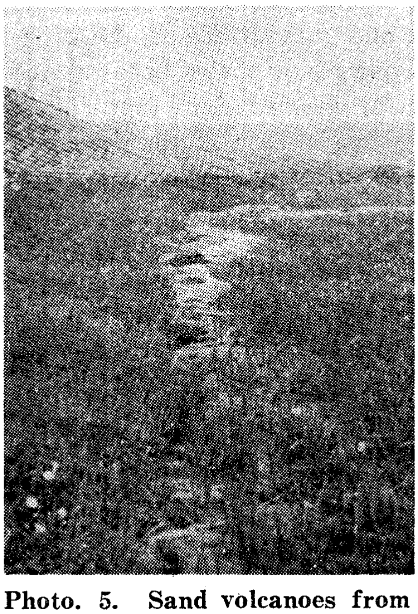


Photo. 5. Sand volcanoes from outside base of river dike (Site C)

Photo. 6. A subsided embankment along the Kitakami Canal (Site I-3)

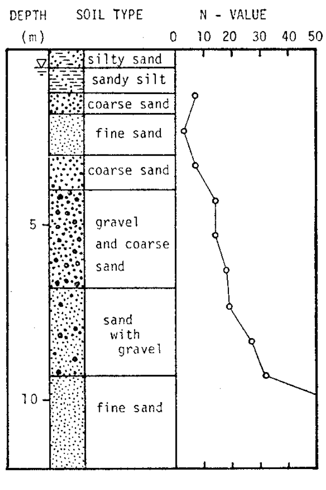


Fig. 4. Soil profile near outside base of the dike at Nakamura (Site F-2). Data from Iwasaki and Tokida (1980)

Photo. 7. Boiled sand at outside base of dike along the Yoshida River (Site Q-1)

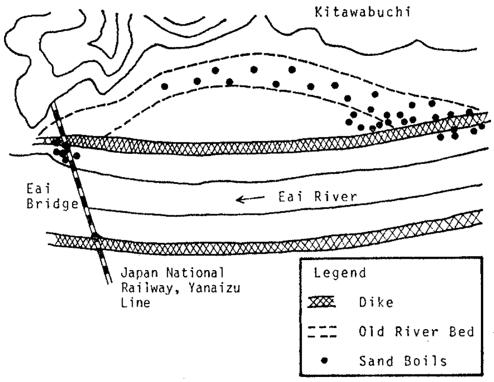


Fig. 5. Locations of liquefaction at the old river bed near the right bank of Eai River (Site P). Data from Hoshihata (1978)

At Ohmagari district in Yamoto Town, a canal embankment was damaged and liquefaction was observed near the embankment (Sites I–3 and I–4). As shown in Photo. 6, the surface of embankment, along the Kitakami Canal, settled to a maximum of 1 m over 30 m to 40 m in length. The boiled sand was found in a paddy field inside the embankment.

As shown in Table 1, liquefaction took place at several sites at the basin of Kitakami River (Site M), Old Kitakami River (Site O), Eai River (Site P) and Yoshida River (Site Q) where settlements and/or cracks of river embankments were induced. Extensive sand volcanoes were found at the inside or outside bases of the dike along Yoshida River as shown in Photo. 7. The surface of the dike settled about 50 cm. Fig. 5 shows the locations of sand volcanoes at the old river bed near the right bank of Eai River in the Kitawabuchi District (Site P). The surface and the slope of the bank cracked at the site of the entrance to the old river bed. However, the surface of the bank did not subside. It is noticed that most of the sites of liquefaction are located on the old river bed.

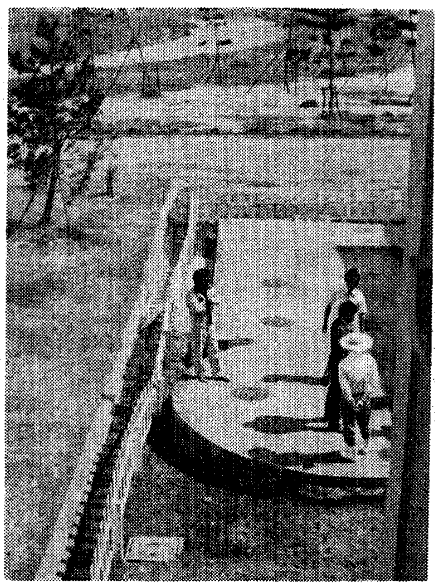


Photo. 8. An uplifted buried sewage treatment tank behind the National Recreation Center (Site A-4)

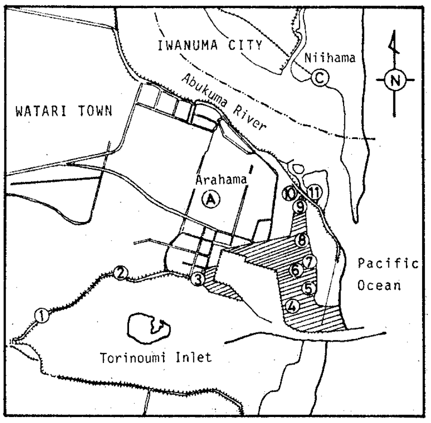


Fig. 6. Enlarged map of the liquefaction sites near the mouth of Abukuma River

Liquefaction Sites Where Structures were Damaged

Liquefaction sites near the mouth of Abukuma River are shown in Fig. 6. The hatched zone in this figure shows the land reclaimed during 1946 through 1947. Most of the liquefaction sites are located within this reclaimed area.

Behind the National Recreation Center (Site A-4), a buried sewage treatment tank, 12.5 m in length, 3.7 m in width, and 1.55 m in depth, which had been buried 1.35 m in the ground and contained 65 cm of sewage, was uplifted by 20 to 30 cm and was subjected to great damage (see Photo. 8). The grain size distribution of this liquefied sand is shown in Fig. 14.

In Torinoumi Park, some liquefaction was observed: the central part of the bottom of a swimming pool (Site A-5) was bent into a convex shape by uplift forces, and sand boiled out through cracks along the edges of the pool. As shown in Photos. 9 to 12, a large amount of sand spewed out from fissures in an athletic field (Site A-6) and in a baseball park (Site A-7), and a public lavatory (Site A-7) tilted by several degrees. Witness near the sites told us that the ground surface, at first, had swelled about 60 cm, then sand and water had boiled out. Many sand volcanoes were observed and houses

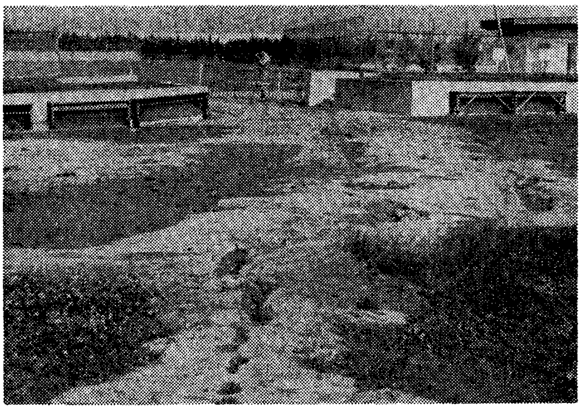


Photo. 9. Boiled sand from fissures in an athletic field (Site A-6)

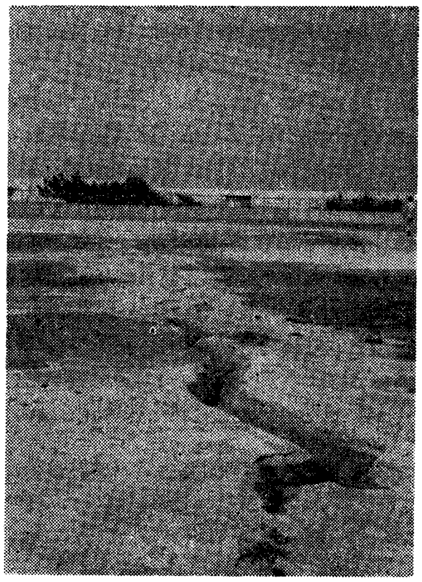


Photo. 10. Sand spewed out from a fissure in a baseball park (Site A-7)

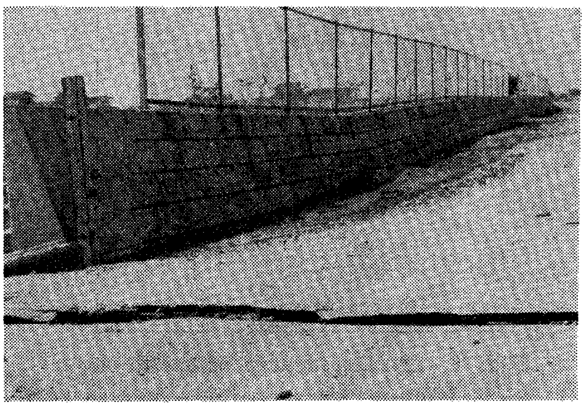


Photo. 11. Damaged fence of an athletic field by soil liquefaction (Site A-6)

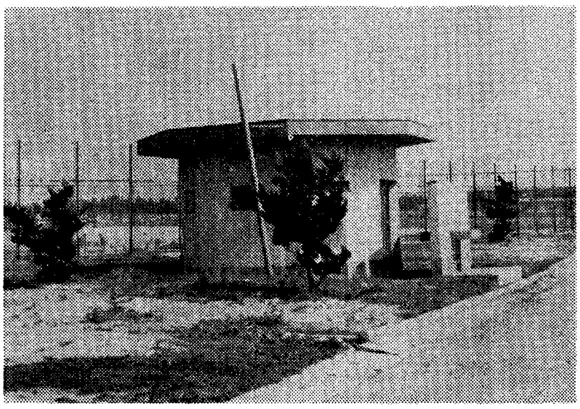


Photo. 12. A slightly tilted public lavatory near baseball park (Site A-7)

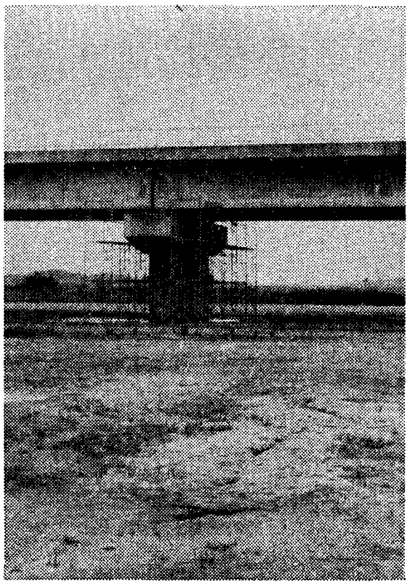


Photo. 13. **Boiled sand from fissures parallel to the river near the Yuriage-Ohashi Bridge (Site D)**

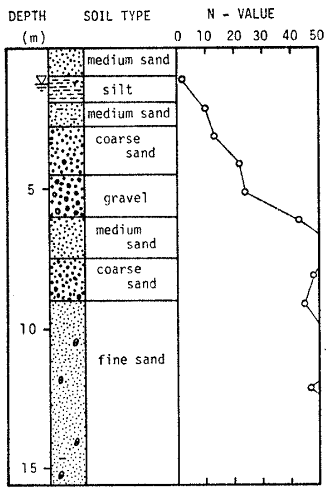


Fig. 7. Soil profile at river bed of Natori River near the Yuriage-Ohashi Bridge (Site D). Data from Iwasaki and Tokida (1980)

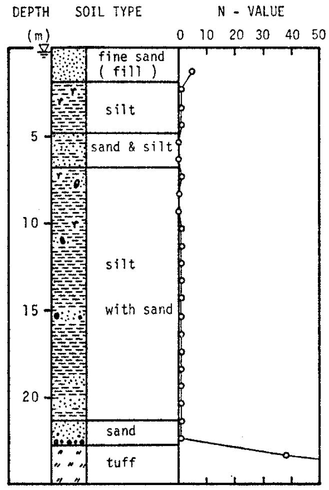


Fig. 8. Soil profile near a pumping house (Site G-1). Data from Matsushima Town

slightly tilted due to liquefaction at Arahama in Watari Town.

Liquefaction occurred along Natori River in the vicinity of Natori City. The dry river bed was cracked parallel to the river near Yuriage-Ohashi Bridge, and liquefied sands spewed out from these cracks (Site D) as shown in Photo. 13. Some cracks were found near the piers of the Yuriage-Ohashi Bridge and the ground around the piers settled. It is likely that these cracks near the piers have been caused by liquefaction. Fig. 7 shows a representative soil profile at the site of dry river bed near the Yuriage-Ohashi Bridge (Iwasaki and Tokida, 1980). As shown in Fig. 14, the boiled soil was a poorly graded coarse sand.

At Matsushima Town, liquefaction was induced at the seashore and at reclaimed land. At Takagi district in Matsushima Town (Site G-1), boiled sand was observed around a pumping house and a sewage treatment tank located about 50 m from Takagi River. As shown in Photo. 14, the pumping house tilted about 10 degrees and settled due to liquefaction, the buried sewage treatment tank was floated and the surrounding ground slightly settled. Before being reclaimed during 1956 through 1957, this area had been used as a salt field. Fig. 8 shows a soil profile at the site near the sewage treatment tank. From this figure, it can be seen that the ground water table was shallow, only 20 cm below the ground surface. The result of a sieve analysis of this liquefied sand is shown in Fig. 14.

At Ohmagari-hama Beach, the place around a sports field was covered with numerous sand volcanoes and the field subsided tens of centimeters (Site I-1). Most of sands boiled out from cracks of surface layers. However, the shapes of a few of them were unusual: dried clayey surface layers were broken and were dispersed into clods of about 20 cm by pressure of the eruption of water and sand (see Photo. 15). Before being reclaimed recently, this site had been a lagoon. Sand volcanoes and cracks were also observed along a sea bank (see Photos. 16 and 17) which had tilted slightly and had been moved several centimeters toward the sea (Site I-2). The grain size distributions of these liquefied sands are shown in Fig. 14.

At Kohyo Town, a great amount of sand which had boiled out from cracks were seen around the Kohyo Elementary School (Site J-1) and some houses (Site J-2). Some of these houses were slightly uplifted, and others subsided nonuniformly. This area was reclaimed

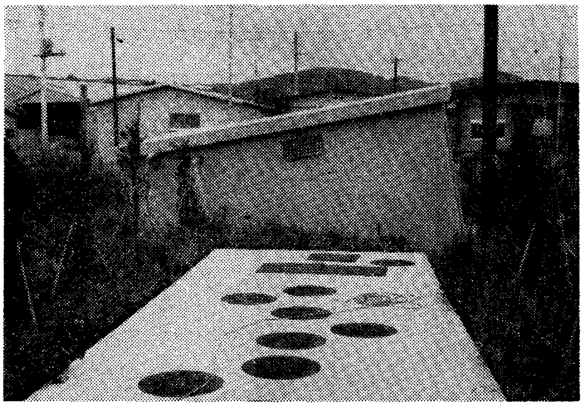


Photo. 14. A tilted pumping house and a floated buried sewage treatment tank (Site G-1)

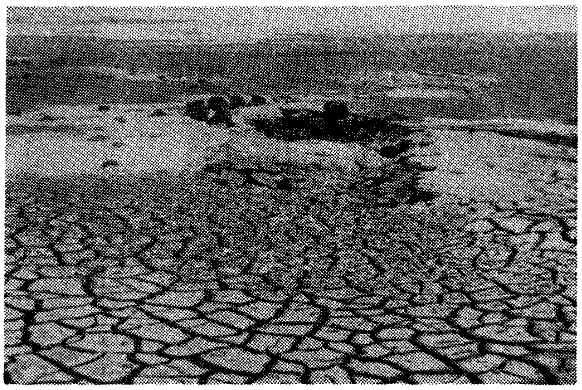


Photo. 15. A broken clayey surface layer by the eruption of water and sand in sports field at Ohmagari-hama Beach (Site I-1)

Photo. 16. A typical sand volcano at Ohmagari-hama Beach(Site I-2)

Photo. 17. Sand volcanoes inside a sea bank at Ohmagari-hama Beach (Site I-2)

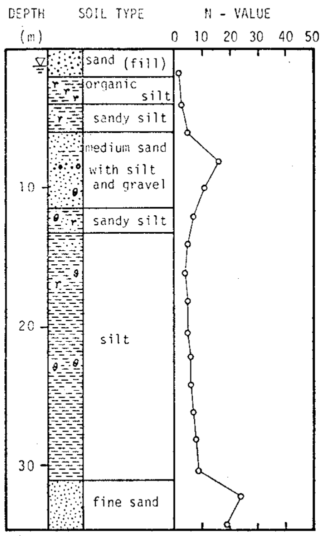


Fig. 9. Soil profile at Kohyo Town (Site J-1). Data from Ishinomaki City

in 1965 using sand taken from the bed of Kitakami River. Previously it had been a backmarsh of Old Kitakami River and utilized as a paddy field. Judging from the soil profile shown in Fig. 9, the reclaimed sand which lies just beneath the ground surface must have liquefied.

At Ishinomaki Port (Site K-1), liquefaction took place (Tsuchida et al., 1979) at the Nakajima-Quay, at the Hiyori-Quay and at the Shiomi-Quay. These quays were constructed during 1968 through 1972. The quay walls moved toward the sea (a maximum of 116 cm), and concrete roads of the quays cracked and settled. Some boiled sands were also observed at these spots. Similarly, sand volcanoes were observed and a quay wall tilted at Ishinomaki Fishing Port (Site K-2).

Liquefaction Sites Where Structures or Earth Structures were not Damaged

The soil profile with N-values at the Arahama Gesuiro Sewage plant (Site A-9) in 1974 is shown in Fig. 10. It shows that the Arahama area is covered with very soft sandy deposits, about 9 m in thickness, whose N-values are generally less than 10. It is observed that many sand volcanoes had formed and houses had slightly tilted due to liquefaction around the Arahama Gesuiro sewage plant. The Arahama Gesuiro sewage plant was not damaged even though the surrounding ground settled about 20 cm, as shown in Photo. 18. The sewage plant was supported by 437 prestressed concrete piles, 300 mm in diameter and 8 to 13 m in length at each node of a triangular mesh with a spacing of 2 m. Therefore, it was concluded that the sewage plant remained intact because of its strong foundation.

Several sand volcanoes were also observed around the National Recreation Center (Site A-4), which had been built approximately ten years ago. This building was not damaged owing to its foundation consisting of 167 concrete piles more than 6 m in length. However, the buried sewage treatment tank behind this building was uplifted by liquefaction as described before.

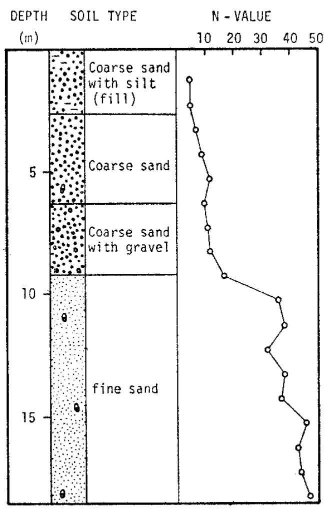


Fig. 10. Soil profile at the Arahama Gesuiro Sewage Plant (Site A-9). Data from Watari Town

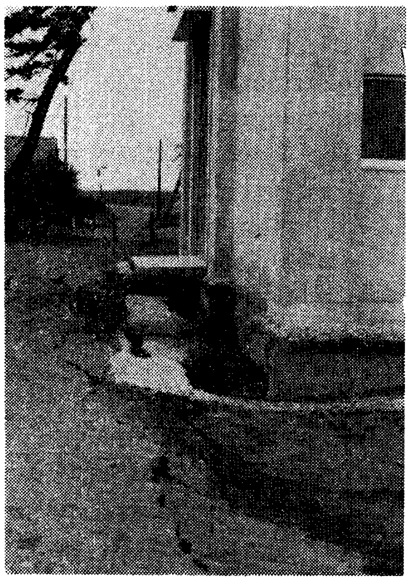


Photo. 18. An undamaged sewage plant (Arahama Gesuiro), and subsided surrounding ground (Site A-9)

At Ishinomaki Fishing Port (Site K-2), sand volcanoes were observed near a tilted quay wall of 7 m in height. However no sand volcanoes were observed near oil storage tanks, 6 000 kl, 1 500 kl and 500 kl in capacity, located just behind the wall, and the tanks were not damaged (Ishihara et al., 1980). The ground of this tank yard had been improved by sand compaction piles, 700 mm in diameter, drived on a 1.8 m triangular spacing. Therefore it may be concluded that the sand compaction piles prevented liquefaction.

Photo. 19. Sand volcanoes and settlement at backshore along Suzaki-hama Beach (Site H)

In addition, sand volcanoes were also observed near the piers of the Abukuma Bridge of the Johban Railway (Site B), the Natori Bridge (Site E) and at the base of the New Tohoku Railway (Site R), but these structures were not damaged due to liquefaction.

Numerous sand volcanoes and settlement extended over 500 m at the backshore along the coastline of the Suzaki-hama Beach (Site H) in Naruse Town (see Photo. 19). Though water is seen in this photograph, it is judged that water was not the sea water but that which spewed out from under the ground because the ground surface in this area was above sea level. The grain size distribution of the sand volcano is shown in Fig. 14.

At Kawamae (Site N), sand volcanoes were observed at the both sides of the base of the river dike, although the dike had suffered no damage.

EVALUATION OF LIQUEFIED LAYERS BY SEDIMENTARY ENVIRONMENTS OF BOILED SANDS

Methods for identifying liquefied soil layers may be classified into two groups: a) by comparing the grain size distribution of a sand boil with that of the in situ sand b) by comparing the results of undrained cyclic shear tests on undisturbed samples with the dynamic shear stresses to be induced during earthquakes. The method a) has been implemented by visually comparing the grain size distribution curves in a rather quantitative manner. The authors attempt to improve the reliability of the method by introducing grain size frequency distribution curves which have been used in the field of geography. For that reason, the sieve analyses for the present paper were conducted with special care by adding intermediate size sieves.

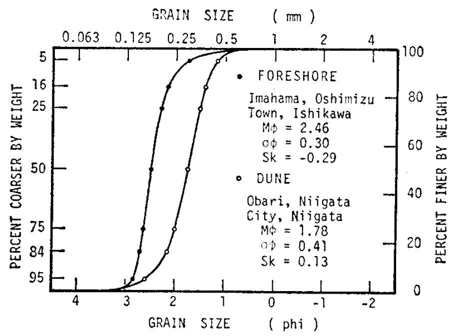


Fig. 11. Grain size distribution curves of typical samples of foreshore and dune sand

Inman (1952), Folk and Ward (1957), Friedman (1961), Uesugi (1972) and others have reported that grain size frequency distributions are closely related to sedimentary environments. Values of sorting and skewness determined from samples of sand are more valuable in determining regional variations than in environmental interpretation. Each textural parameter, which is based on the shape of size-frequency curve, was measured by Folk and Ward's method (graphic measure), as shown in Fig. 11. Equations to be used in the calculation are as follows:

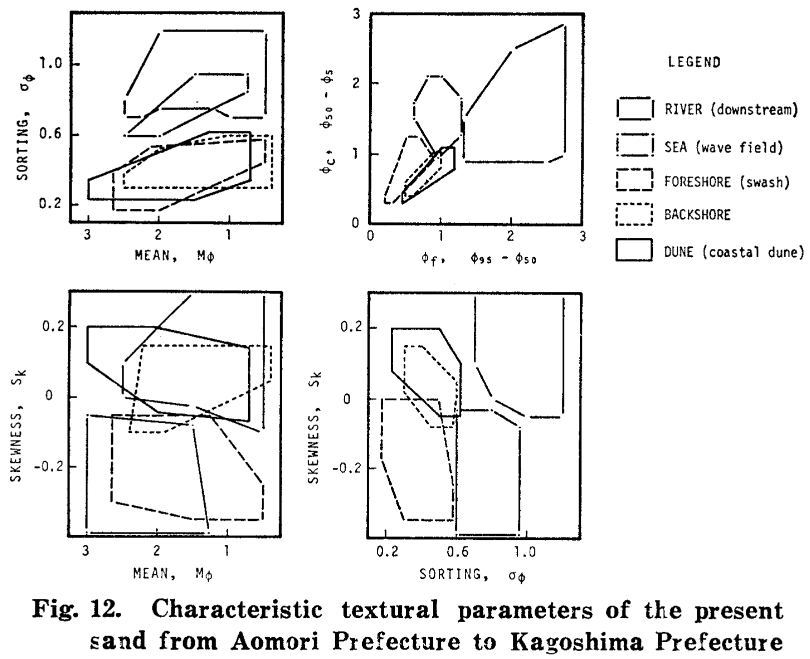


Fig. 12. Characteristic textural parameters of the present sand from Aomori Prefecture to Kagoshima Prefecture by Tohno (1979)

$$\text{Mean:} \quad M_\phi = \frac{(\phi_{84}+\phi_{50}+\phi_{16})}{3}$$

$$\text{Sorting:} \quad \sigma_\phi = \frac{(\phi_{84}-\phi_{16})}{4} + \frac{(\phi_{95}-\phi_5)}{6.6}$$

$$\text{Skewness:} \quad S_k = \frac{(\phi_{84}+\phi_{16}-2\phi_{50})}{2(\phi_{84}-\phi_{16})} + \frac{(\phi_{95}+\phi_5-2\phi_{50})}{2(\phi_{95}-\phi_5)}$$

$$\phi = -\log_2 d$$

where d is grain size in mm and ϕ_x is the grain size, at $x\%$ coarser by weight. Correlation between the textural parameters from samples of the Japanese present sand is shown in Fig. 12. Here the encircled areas indicate the characteristics area of present sand for each sedimentary environment from Aomori Prefecture to Kagoshima Prefecture summarized by Tohno (1979).

Fig. 13 shows the grain size frequency distributions of the present sands in Miyagi Prefecture. This figure shows that the test results of all the samples in Miyagi Prefecture lie within their indicated encircled areas for each sedimentary environment (as shown

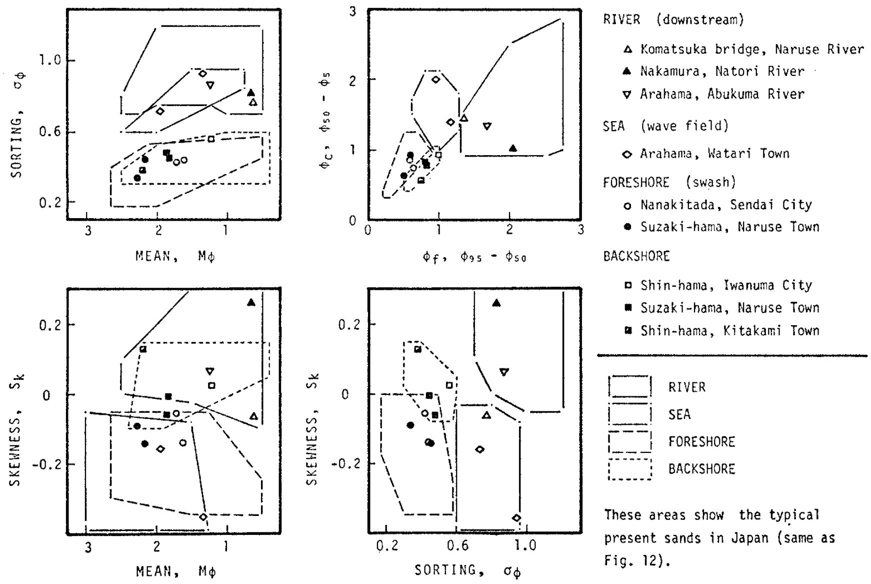
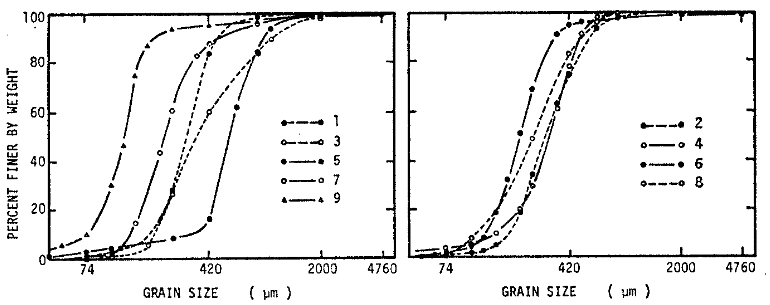


Fig. 13. Textural parameters of present sands in Miyagi Prefecture



1. National Recreation Center (A-4)
2. Torinoumi Athletic Field (A-6)
3. Bar near the Mouth of Abukuma River (A-11)
4. River bank of Abukuma River (C)
5. River bed of Natori River (D)
6. Pumping House (G-1)
7. Suzaki-hama Beach (H)
8. Ohmagari-hama Sports Field (I-1)
9. Ohmagari-hama Beach (I-2)

Fig. 14. Grain size distribution curves of liquefied sands by the 1978 Miyagiken-Oki earthquake

in Fig. 12). Therefore, the sedimentary environment can be inferred from these grain size frequency distributions.

It is attempted to infer the sedimentary environment of the liquefied sands from these grain size frequency distribution. The grain size distribution curves of liquefied sands by the 1978 Miyagiken-Oki earthquake are shown in Fig. 14. Textural parameters of liquefied sands were derived from Fig. 14 and are shown in Fig. 15. The sedimentary environment of the liquefied sands was deduced based on the characteristics patterns shown in Fig. 15 by Tohno's method (Tohno, 1979). One can estimate the environment of sedimentation of a

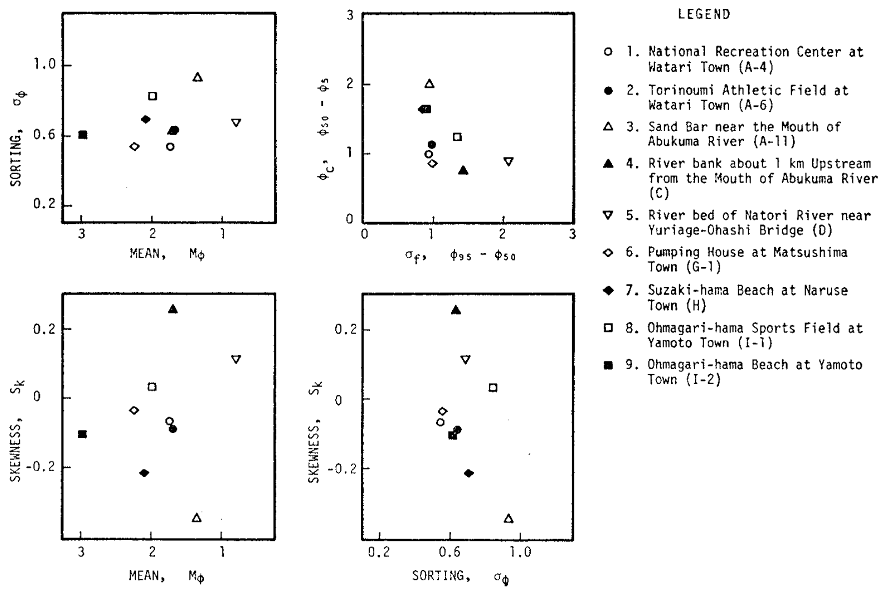


Fig. 15. Textural parameters of liquefied sands by the 1978 Miyagiken-Oki eathquake

Table 3. Depositional environments of boiled sands by Tohno's method (Tohno, 1979)

Liquefaction Site	National Recleation Center				Torinoumi Athletic Field				Bar near the Mouth of Abukuma R.				River bank of Abukuma River				River bed of Natori River				Pumping House			
	A-4				A-6				A-11				C				D				G-1			
Textural Parameters	$\sigma\phi \cdot M\phi$	$S_k \cdot M\phi$	$S_k \cdot \sigma\phi$	$\phi_c \cdot \phi_f$	$\sigma\phi \cdot M\phi$	$S_k \cdot M\phi$	$S_k \cdot \sigma\phi$	$\phi_c \cdot \phi_f$	$\sigma\phi \cdot M\phi$	$S_k \cdot M\phi$	$S_k \cdot \sigma\phi$	$\phi_c \cdot \phi_f$	$\sigma\phi \cdot M\phi$	$S_k \cdot M\phi$	$S_k \cdot \sigma\phi$	$\phi_c \cdot \phi_f$	$\sigma\phi \cdot M\phi$	$S_k \cdot M\phi$	$S_k \cdot \sigma\phi$	$\phi_c \cdot \phi_f$	$\sigma\phi \cdot M\phi$	$S_k \cdot M\phi$	$S_k \cdot \sigma\phi$	$\sigma_c \cdot \phi_f$
River (Downstream)	△	△	△	△	△	△	△	△	○	×	×	×	△	○	△	△	○	○	○	○	△	△	△	△
Sea (Wave field)	△	△	△	○	△	○	○	○	○	○	○	○	△	×	×	×	△	×	×	×	△	△	△	△
Foreshore	○	△	△	△	△	○	△	△	×	○	×	×	△	×	×	×	△	×	×	×	△	△	△	△
Backshore	○	○	○	○	△	△	△	△	×	×	×	×	△	×	×	×	△	○	△	×	△	○	○	○
Dune	○	△	△	△	△	△	△	△	×	×	×	×	△	△	△	×	△	○	△	×	△	△	○	○

Liquefaction Site	Suzaki-hama Beach				Ohmagari-hama Sports Field				Ohmagari-hama Beach			
	H				I-1				I-2			
Textural Parameters	$\sigma\phi \cdot M\phi$	$S_k \cdot M\phi$	$S_k \cdot \sigma\phi$	$\phi_c \cdot \phi_f$	$\sigma\phi \cdot M\phi$	$S_k \cdot M\phi$	$S_k \cdot \sigma\phi$	$\phi_c \cdot \phi_f$	$\sigma\phi \cdot M\phi$	$S_k \cdot M\phi$	$S_k \cdot \sigma\phi$	$\phi_c \cdot \phi_f$
River (Downstream)	△	×	×	×	○	○	○	○	△	×	△	△
Sea (Wave field)	○	○	○	○	△	△	×	×	△	△	○	○
Foreshore	△	○	△	×	×	△	×	×	×	△	△	×
Backshore	×	△	△	×	×	○	×	×	×	△	△	×
Dune	×	×	×	×	×	○	×	×	×	×	△	×

○: Observed data points fall within the enclosed area in Fig. 12
△: Observed data points lie just outside the enclosed area in Fig. 12
×: Observed data points lie far outside the enclosed area in Fig. 12

soil by superimposing Fig. 12 over Fig. 15. For example, all the open square symbols in Fig. 15 fall into the area enclosed by dashed lines, indicating that the soil is a river sand. The soil samples that can be identified in this manner are so indicated by circles in Table 3.

At the mouth of Abukuma River (Sites A and C), all the sand is fine-grained with a mean particle size, D_{50}, of approximately 0.3 mm (see Fig. 14). It can be judged that the liquefied sand at Torinoumi athletic field (Site A-6) is a marine sand, the one at National Recreation Center (Site A-4) is a beach sand, the one at a river dike (Site A-11) is a marine sand of wave field, and the one at a river dike (Site C) is a river sand of downstream by Table 3. It is considered that the liquefied sands at Site A-4 and Site A-6 are hydraulic fill consisting of marine and beach sands, as these sites are located within a reclaimed area (see Fig. 6).

As shown in Fig. 14, the liquefied sand at the Yuriage-Ohashi Bridge was a poorly graded coarse sand with a mean particle size, D_{50}, of 0.5 mm. This liquefied sand is judged to be a river sand by Table 3. Therefore, the depositional environment of the liquefied sand is the same as that for a surface deposit which lies on the river bed. Comparing the grain size distribution of the liquefied sand with those of the in-situ soils based on the sieve analysis by Iwasaki et al. in 1980, it can be concluded that the liquefied sand is similar to the sandy deposits encountered at depths ranging from 1.8 m to 3.0 m.

At a pumping house in Matsushima Town, the liquefied sand must be a beach sand (backshore and/or dune), judging from its grain size frequency distribution as shown in Table 3. It can be concluded that a sand layer between the ground surface and the depth of 2 m liquefied (see Fig. 8). This sand layer is a man-made layer, while the sand deposits from 4.5 m to 7 m in depth are fluvial deposits.

At Suzaki-hama Beach and at Ohmagari-hama Beach, liquefied sands contained few pumices and were a poorly graded fine-grained sand, with the mean particle size, D_{50}, of approximately 0.5 mm. Judging from the textural parameters of the both liquefied sands, it is concluded that the sands were not backshore sands, but sea sands.

At Ohmagari-hama sports field, the textural parameters of the liquefied sand indicates that sand was not of a lagoon origin, but a river sand. Therefore, the sand fill, which had been transported from a river, probably liquefied.

The sedimentary environment of liquefied sands near river banks can be estimated from the textural parameters by Tohno's method. This is shown in Table 4. The grain size distribution of these sands was based on the sieve analysis by Iwasaki et al. in 1980. This table shows that all of the liquefied sands are judged to be fluvial. It is found that the textural parameters of liquefied sands are similar to that of the insitu sandy deposits

Table 4. Depositional environments of boiled sands near river dike by Tohno's method (Tohno, 1979)

Liquefaction Site	Natori River Nakamura Inside dike				Natori River Nakamura Outside dike				Old Kitakami River Oiri Outside dike				Old Kitakami River Oiri Inside dike				Eai River Kitawabuchi Inside dike				Eai River Kitawabuchi Outside dike			
	F				F				O-1				O-2				P				P			
Textural Parameters	$\sigma\phi \cdot M\phi$	$S_k \cdot M\phi$	$S_k \cdot \sigma\phi$	$\phi_c \cdot \phi_f$	$\sigma\phi \cdot M\phi$	$S_k \cdot M\phi$	$S_k \cdot \sigma\phi$	$\phi_c \cdot \phi_f$	$\sigma\phi \cdot M\phi$	$S_k \cdot M\phi$	$S_k \cdot \sigma\phi$	$\phi_c \cdot \phi_f$	$\sigma\phi \cdot M\phi$	$S_k \cdot M\phi$	$S_k \cdot \sigma\phi$	$\phi_c \cdot \phi_f$	$\sigma\phi \cdot M\phi$	$S_k \cdot M\phi$	$S_k \cdot \sigma\phi$	$\phi_c \cdot \phi_f$	$\sigma\phi \cdot M\phi$	$S_k \cdot M\phi$	$S_k \cdot \sigma\phi$	$\phi_c \cdot \phi_f$
River (Downstream)	○	○	○	○	○	○	○	○	○	○	○	○	△	○	△	○	○	○	○	○	○	○	○	○
Sea (Wave Field)	△	×	×	×	△	×	×	×	○	×	×	×	△	×	×	×	△	×	×	×	×	△	×	×
Foreshore	×	×	×	×	×	×	×	×	×	×	×	×	△	×	×	×	×	×	×	×	×	△	×	×
Backshore	×	△	×	×	×	△	×	×	×	△	×	×	△	△	△	×	×	×	×	×	×	△	×	×
Dune	×	○	×	×	×	○	×	×	×	○	△	×	△	○	△	×	×	×	×	×	×	△	×	×

○: Observed data points fall within the enclosed area in Fig. 12
△: Observed data points lie just outside the enclosed area in Fig. 12
×: Observed data points lie far outside the enclosed area in Fig. 12

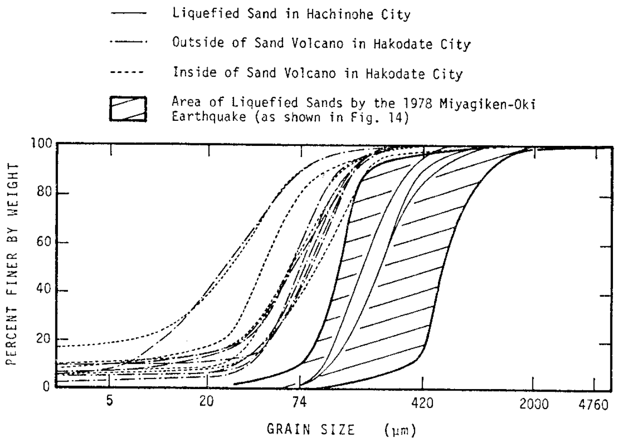


Fig. 16. Grain size distribution curves of liquefied sands by the 1968 Tokachi-Oki earthquake. Data from Research Committee on Earthquake Damage of the Japanese Society of Soil Mechanics and Foundation Engineering (1968)

as follows: these sandy deposits are 1.4 m to 3.0 m in depth at Nakamura (Site F-2), 4.5 m to 7.0 m in depth at Oiri (Site O-2), 3.3 m to 5.0 m in depth at Kitawabuchi (Site P).

On the basis of Tables 3 and 4, the textural parameters of liquefied sands fall into the following ranges: the means (M_ϕ) from 0.5 to 3.0, the sorting (σ_ϕ) from 0.5 to 1.2, the skewness (S_k) from −0.33 to 0.32, $\phi_{50}-\phi_5$ from 0.7 to 2.2, and $\phi_{95}-\phi_{50}$ from 0.8 to 2.3. Considering the relatively narrow ranges one may conclude that the liquefied sands are moderately sorted with the mean diameters ranging from 0.1 to 0.8 mm.

Fig. 16 shows the grain size distribution curves of liquefied sands by the 1968 Tokachi-Oki earthquake (Data from the Research Committee on Earthquake Damages of the Japanese Society of Soil Mechanics and Foundation Engineering, 1968). Here the shadowed portion is the area of grain size distribution of liquefied sands by the 1978 Miyagiken-Oki earthquake (see Fig. 14). This figure shows that the grain size distribution curves of liquefied sands in Hachinohe City fall within the grain size area of liquefied sands by the 1978 Miyagiken-Oki earthquake. Compared with the liquefied sands during the 1978 Miyagiken-Oki earthquake, however, the liquefied sands during the 1968 Tokachi-Oki earthquake had in general smaller grain size.

EVALUATION OF LIQUEFIED LAYERS BY DETAILED INVESTIGATIONS

After the Miyagiken-Oki earthquake, several detailed soil investigations were carried out where liquefaction was induced, and resultant damages of structures were studied. Iwasaki and Tokida (1980) identified the liquefied layers at Yuriage (Site D), Yuriage-Kami (Site F-1) and Nakamura (Site F-2), based on the results of borings, cyclic triaxial tests, dynamic response analyses and liquefaction analyses. Ishihara et al. (1980) carried out borings, cyclic triaxial tests and liquefaction analyses, and compared the liquefaction potential of an improved soil yard with that of the original yard at Ishinomaki Port (Site K-2). The Tohoku Regional Construction Bureau made several borings at liquefaction sites. Yasuda and Tokida (1980) evaluated the liquefied layers at these sites by simple analyses using the *N*-values and mean particle diameters of soil obtained from the bureau's borings.

As stated in the previous section the grain size distributions of boiled sands were obtained at two sites (Site D and Site F-2) where liquefaction analyses were conducted by Iwasaki and Tokida. Therefore, these grain size distributions were compared with the grain sizes obtained by the authors in order to determine the depth of the liquefaction layer. The authors estimate the liquefied layer lies between 1.8 m and 3 m in depth at Yuriage (Site D) and between 1.4 m and 3 m in depth at Nakamura (Site F-2). Iwasaki and Tokida estimated the liquefied layers at Yuriage and at Nakamura to have been between 2 m and 5 m in depth and between 2 m and 7 m, respectively. The authors evaluated the liquefied layers based on the boiled sands. However, considering the fact that the liquefied sand does not necessarily spew out, the estimated liquefaction layers by the authors may be thinner than those by Iwasaki et al.. Therefore, the depths of the liquefied layers estimated by the two methods are fairly similar.

CONCLUSIONS

Liquefaction was observed at 38 sites during the Miyagiken-Oki earthquake of June 12, 1978. At 16 sites, damages to earth structures, such as settlement of river dikes or inlet dikes and subsidence of a residential area, were observed. An inlet dike settled as much as 1.6 m. At 12 sites, structural damages, such as tilting of quay walls and a pumping house and uplifting of sewage tanks, were observed. Most structures which had firm foundations, e.g., piles or improved ground, were not significantly damaged.

Based on the grain size distributions of liquefied sands, depths and environments of the liquefaction layers at several sites could be evaluated. Most soils that liquefied were either river sands or reclaimed sands.

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