SITES OF RELIQUEFACTION CAUSED BY THE 1983 NIHONKAI-CHUBU EARTHQUAKE

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ABSTRACT

The Nihonkai-chubu Earthquake, with a magnitude of 7.7, occurred on May 26, 1983 in northwest Japan and produced liquefaction sites in the coastal plain of Akita and Aomori Prefectures. About one month later, the maximum aftershock, with a magnitude of 7.1, again induced liquefaction at several sites in Aomori Prefecture. The authors surveyed the affected area and discovered almost ten reliquefaction sites. Initial liquefaction at these sites had not occurred solely because of the main shock of the Nihonkai-chubu Earthquake. Initial liquefaction at some sites was attributable to the Niigata Earthquake in 1964, the Tokachi-oki Earthquake in 1968, and other earlier earthquakes. Although it had earlier been thought that the occurrence of reliquefaction would be improbable, the authors' investigation shows that reliquefaction occurs frequently, even when the acceleration caused by a later earthquake was less than that caused by a former earthquake. It can therefore be said that a site liquefied by an earthquake can be reliquefied by a subsequent earthquake.

Key words : earthquake, earthquake damage, hysteresis, liquefaction, site investigation
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INTRODUCTION

It is generally believed that sand grains recede and consolidate after liquefaction, following the emission of excess pore water. Accordingly, it has been assumed loose sand would become dense and resistant to reliquefaction by a subsequent earthquake of about the same magnitude as the earthquake that caused liquefaction. Koizumi (1966) reported that the SPT *N*-values of liquefied loose sand layers in Niigata City increased after the Niigata Earthquake in 1964.

On the other hand, Kuribayashi and

Tatsuoka(1975)identified several sites in Japan where liquefaction might have been induced several times as a result of a number of earthquakes. The accurate positions of those sites, however, were not clear because their research was based not on detailed site surveys but on rough surveys of historical data.

In 1978 the Miyagiken-oki Earthquake caused liquefaction at about 30 sites (Tohno and Yasuda, 1981). The Public Works Research Institute (1983) reported an occurrence of reliquefaction in the Nakamura District, where liquefaction had been induced by the

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preshock of the Miyagiken-oki Earthquake. This indicated that reliquefaction occurs at the same place where liquefaction has taken place. However, the question remained whether reliquefaction is induced by the same, or smaller, acceleration than the previous acceleration, because the acceleration during the main shock of the Miyagiken-oki Earthquake in Nakamura District was greater than the acceleration during the pre-shock.

Several studies on reliquefaction have been conducted using laboratory soil testing methods. Finn et al. (1970) carried out liquefaction and reliquefaction tests using a cyclic simple shear test apparatus and a cyclic triaxial test apparatus. They reported that the resistance to reliquefaction is less than the resistance to liquefaction, although the density becomes great due to consolidation after liquefaction. Tatsuoka et al. (1974) reported, based on cyclic triaxial tests, that if a specimen is consolidated anisotropically after liquefaction it becomes prone to reliquefaction, whereas it becomes resistant to reliquefaction when the consolidation is done isotropically. By using cyclic simple shear tests, Matsuoka et al. (1985) also pointed out the effect of consolidation methods on susceptibility to reliquefaction.

Sasaki and Taniguchi (1982) performed large-scale shaking table tests, using ground models 12 m in length, 3 m in depth, and 2 m in width, to study the effectiveness of a gravel drain in preventing liquefaction. In these tests, they carried out cone penetration tests before and after liquefaction and showed that the cone resistance of the deeper part of the sand layer increased, whereas that of the shallower part decreased. From this result they estimated that the settlement of ground does not result in uniform compaction of a sand layer with depth.

Though several studies on reliquefaction have been conducted, as mentioned above, it is still uncertain whether liquefied sand becomes resistant to reliquefaction. However, the Nihonkai-chubu Earthquake in 1983 produced several reliquefaction sites in Akita and Aomori prefectures. Based on detailed

surveys of liquefaction sites after the earthquake, the authors identified reliquefaction sites. The frequent earthquakes which had occurred in both prefectures before the Nihonkai-chubu Earthquake had induced liquefaction, and the maximum aftershocks caused some reliquefaction.

In this paper, the seismic intensity and damage to structures on reliquefaction sites during the Nihonkai-chubu and related earthquakes are described. Through analyses of liquefaction at these sites, the authors also tried to estimate the depths of liquefied soil layers.

THE 1983 NIHONKAI-CHUBU EARTHQUAKE

On May 26, 1983, northwestern Japan was shaken by the Nihonkai-chubu Earthquake, which had a magnitude of 7.7. The epicenter of the earthquake was about 90 km west of Noshiro City in Akita Prefecture, as shown in Fig. 1. At many locations in the coastal plain of Akita Prefecture and Aomori

Fig. 1. Distribution of sites of liquefaction and reliquefaction caused by the Nihonkai-chubu Earthquake

Fig. 2. Epicentral distribution of earthquakes inducing liquefaction

Prefecture, sand liquefaction was induced (Tohno, Yasuda and Shamoto, 1983; Tohno and Shamoto, 1986).

After the main shock of the Nihonkai-chubu Earthquake, many aftershocks occurred in an area about 150 km long and about 50 km wide, as shown in Fig.1. The number of aftershocks amounted to about 9000 by the end of July. On June 21, the maximum aftershock, with a magnitude of 7.1, occurred about 100 km west of the Tsugaru Peninsula and caused reliquefaction at several sites in the peninsula where liquefaction had taken place during the main shock.

SITES OF LIQUEFACTION CAUSED BY THE 1983 NIHONKAI-CHUBU EARTHQUAKE AND OTHER EARTHQUAKES

The authors started to discover liquefaction sites and to investigate damage to structures due to liquefaction on May 28, two days after the main shock of the Nihonkai-chubu Earthquake. The investigation included a site survey, interviews with local residents, and an aerial-photograph survey of Akita Prefecture and Aomori Prefecture. Fig.1 shows the liquefaction sites included in this investigation. Most of the sites of liquefaction caused by the main shock had been

identified by June 21, when the maximum aftershock occurred.

A few hours after this aftershock, the authors began to search for liquefaction sites in the Tsugaru Peninsula, the area which had experienced the most severe ground shaking of any point in either prefecture. According to the accounts the local residents, the authors judged that liquefaction had been induced at seven sites, numbered 4 to 10 in Fig.1. Liquefaction had occurred at all these sites as a result of the main shock about one month previously.

Akita Prefecture and Aomori Prefecture have comparatively high seismic activity and have many earthquakes. A review of the literature on earthquakes from 1939 to 1983 clarified that the six sites numbered 1, 2, 3, 4, 6 and 11 in Fig.1 and experienced liquefaction earlier.

It was concluded that reliquefaction had been induced during the main shock and the aftershock of the Nihonkai-chubu Earthquake at the eleven sites shown in Fig.1 and Table 1. These sites are described in detail in the following section.

LIQUEFACTION-INDUCED DAMAGE AT RELIQUEFACTION SITES

Arayamotomachi Town in Akita City

At Arayamotomachi Town in Akita City, liquefaction was caused in a long and narrow area by the main shock of the Nihonkai-chubu Earthquake. Due to this liquefaction, houses settled, telegraph poles sank, and sewage tanks rose to the ground surface. The damage was concentrated in a small zone about 100 m in width and 500 m in length, in an area of land recently reclaimed over an old river by filling with sand from adjacent sand dunes.

According to a soil investigation conducted by Kawashima et al. (1984) after the Nihonkai-chubu Earthquake at a point near the center of the liquefied area, a layer of very loose fine sand, with SPT *N*-values of 0 to 6, forms a deposit extending from the ground surface to about 6 m in depth, as

Table 1. Sites of reliquefaction caused by several earthquakes

Prefecture	City, Town or Village	District	No.	Liquefaction						
				OG*	AO	NG	OO	TO	NM	NA
Akita	Akita City, Arayamotomachi Town		1			○			●	
	Wakami Town	Tamanoike	2	○	●				●	
	Ohgata Village	Hachirogata reclaimed land, Dike	3		○	●	●	○	●	
Aomori	Shariki Village	Tomiyachi	4					○	●	●
	Shariki Village	Shimoushigata	5						○	●
	Nakazato Town	Tomino(Takeda Elementary School)	6					○	●	●
		Ashino	7						○	●
		Takeda	8						○	●
	Kanagi Town	Makita	9						○	●
	Kizukuri Town	Tateoka	10						○	●
	Aomori City	Aomori Station	11					○	●	

* OG : Oga Earthquake (1939, M=7.0), AO : Aomorikenseiho-oki Earthquake (1964, M=6.9), NG : Niigata Earthquake (1964, M=7.5), OO : Oga-oki Earthquake (1964, M=8.3), TO : Tokachi-oki Earthquake (1968, M=7.9), NM : Nihonkai-chubu Earthquake (1983, M=7.7, main shock), NA : Nihonkai-chubu Earthquake (1983, M=7.1, aftershock)

** ○ : Liquefaction ● : Reliquefaction

* F_L : factor of liquefaction resistance analyzed by Iwasaki et al.'s method.

** : data of soil condition and F_L -values during the Nihonkai-chubu Earthquake are quoted from Kawashima et al.'s report (1978).

Fig. 3. Soil profile and results of liquefaction analysis at Arayamotomachi in Akita City

shown in Fig. 3. The water table is very shallow, only 1.0 m in depth. Kawashima et al. analyzed liquefaction potential by the simplified method introduced by Iwasaki et al. (1978), as shown in Fig. 3, and estimated that the loose fine sand layer might have been liquefied by the earthquake.

Kitsunezaki (1984) reported that during the 1964 Niigata Earthquake liquefaction was induced at four points just inside the area liquefied by the 1983 Nihonkai-chubu Earth-

quake. He also stated that the sand volcanos which had erupted during the Niigata Earthquake had small craters, whereas those which erupted during the Nihonkai-chubu Earthquake had big ground fissures.

The open squares in Fig. 3 show the liquefaction resistances, F_L , during the Niigata Earthquake; these values were estimated by the authors using the Iwasaki method. The maximum surface acceleration was assumed to be 90.6 gals based on the value recorded at the Akita Prefectural Government building 4 km from Arayamotomachi Town. Because the calculated F_L values exceed 1.0, except for one value recorded at a depth of around 2 m, it is surmised that only a thin soil layer liquefied during the Niigata Earthquake. On the contrary, a soil layer several meters thick is believed to have been liquefied during the Nihonkai-chubu Earthquake, as mentioned above. The difference in thickness of the layers liquefied by the two earthquakes corresponds closely with the difference in intensity of the sand volcanoes.

Tamanoike district in Wakami Town

Tamanoike district in Wakami Town is on the boundary of a sand dune and a low-land zone. The upper soil layer consists of very loose sand, and the ground water table

Fig. 4. Comparison of areas of liquefaction caused by the Oga Earthquake with areas of liquefaction caused by the Nihonkai-chubu Earthquake at Tamanoike District

is very shallow.

According to the report by Miyabe and Takei (1939), sand and water spewed out and cracks and horizontal movements were induced in the locations shown in Fig. 4(a) during the Oga Earthquake of 1939, which had a magnitude of 7.0.

In 1964 reliquefaction was induced by the Aomorikenseiho-oki Earthquake, which had a magnitude of 6.9. Nagumo (1964) reported that water spewed out throughout the Tamanoike district and 36 houses were damaged by irregular settlement.

Reliquefaction was also caused in this district by the main shock of the 1983 Nihonkai-chubu Earthquake. Sand volcanoes were observed in the area as shown in Fig. 4(b). Houses, walls, buried pipe lines, roads and plowed fields were damaged due to the liquefaction. Landslides were also induced toward the Hachirogata west channel.

By comparing Fig. 4(a) and Fig. 4(b), it is evident that reliquefaction was caused by the 1983 Nihonkai-chubu Earthquake in almost the same area as sites the of liquefaction caused by earlier earthquakes.

Hachirogata Polder Dikes

The Hachirogata land reclamation area was

Fig. 5. Damage to the Hachirogata Dike caused by several earthquakes

constructed by filling about 80 percent of the Hachirogata Lagoon, 22,173 hectares in area and 4.5 m in maximum depth, to use as agricultural land. The central part of the reclaimed land, 15,870 hectares in area, is enclosed by three polder dikes: the Front Di-ke, the West Di-ke and the East Di-ke, with lengths of 9.3 km, 22.0 km, and 19.9 km, respectively. The construction of these dikes was started in 1958 and was almost finished in 1964.

In 1960 the Sanriku-oki Earthquake hit a pilot dike, and in 1964 three earthquakes, including the Niigata Earthquake, caused damage again to the polder dikes in the locations shown in Fig. 5. The Tokachi-oki Earthquake damaged the dikes again in 1968. The following descriptions of the damage caused by these earthquakes are partially quoted from the report by the Hachirogata Polder Project Office (1969).

The Sanriku-oki Earthquake, with a magnitude of 7.5, occurred on March 21, 1960, about 300 km east of the Hachirogata La-

goon. During the earthquake a pilot dike under construction settled and sand volcanoes were induced in it. As this damage seemed attributable to liquefaction of the sand fill, improved methods of constructing polder dikes, such as compacting sand fill and expanding the width of the dikes, were discussed. However, these methods were not adopted in the construction of the polder dikes because they were too expensive and their effectiveness could not be evaluated at that time.

A cross section of the West Di-ke is shown in Fig. 6. The dimensions of the other dikes are slightly different. As a fill material, sandy soil of poor grade, as described in Fig. 7, was dredged from the bottom of Hachirogata Lagoon.

In 1964, when the construction of the dikes was almost completed and the reclaimed land was being drained, three big earthquakes hit the dikes. On May 7, the Aomori-oki Earthquake, with a magnitude of 6.9, caused the northwest section of the West Di-ke to settle a maximum of 1.7 m. The resulting top surface of the dike was then only slightly higher than the water level of the West Channel. The length of the damaged dike was 7.7 km. Most parts of the damaged dike settled intact except for cracks on their surface, but some parts of the dike slid toward the West Channel or the reclaimed land. Sand volcanoes were observed everywhere on the damaged dike.

The Niigata Earthquake, on June 16, increased the damage to the West Di-ke. This dike, 6.6 km in length, was formerly identified as a damaged dike. It settled 0.1 m to 0.2 m further than the settlement on May 7. Moreover, an 890 m section of the southwest part of the West Di-ke was newly damaged.

On December 11, the Oga-oki Earthquake hit the Hachirogata reclaimed land and caused counterweight fill to settle 0.3 m along a 40 m section of the West Di-ke.

After the Aomori-oki Earthquake, a study of the mechanism of the damage yielded the following conclusions: damage

Fig. 6. Typical cross section of the western part of the Hachirogata polder dike before and after the 1964 earthquakes

Fig. 7. Grain size distributions of the sand fill and of the boiled sand at Hachirogata reclaimed land

was induced due to liquefaction of the sand fill, and slope failures of the natural ground did not occur because the strength of the natural clay was not reduced by the earthquake. Therefore, the damaged dikes were reconstructed by adding counterweight fill, as shown in Fig. 6, to prevent future damage due to liquefaction.

In 1968, the Tokachi-oki Earthquake, with a magnitude of 7.9, occurred about 365 km east of the Hachirogata reclaimed land area. This earthquake caused the southeast part of the Front Dike to settle a maximum of 1.9 m and caused cracks to open on the asphalt facing and on the roadway on top of the dike. Sand volcanoes were also observed. The damaged portion of the dike was 313 meters long, and this portion was about 300 m from the area where damage had been induced during the Aomorikenseiho-oki Earthquake four years earlier.

In 1983, the main shock of the Nihonkai-chubu Earthquake hit the Hachirogata polder dikes and inflicted damage that was more severe than that caused by previous earthquakes. Asada and Kubo (1983) reported that almost 65 percent of the dikes around the central reclaimed land area settled more than 10 cm. Settlements of dikes, cracks on dike surfaces, and sand volcanoes were observed all over the damaged area, as shown in Photo 1. Dikes were also distorted horizontally and vertically at several points. As shown in Fig. 5, all of the dike portions

Photo. 1. Damage to Hachirogata polder dikes caused by the 1983 Nihonkai-chubu Earthquake

damaged by previous earthquakes were also damaged by the 1983 Nihonkai-chubu Earthquake. It is therefore clear that reliquefaction of the sand fill of the polder dikes was induced by the Nihonkai-chubu Earthquake.

Shimoushigata District of Shariki Village

The maximum aftershock of the 1983 Nihonkai-chubu Earthquake hit the Tsugaru Peninsula on June 21 and caused reliquefaction at several sites. Maximum surface accelerations in the horizontal direction during the main shock and the aftershock at Tsugaru-ohashi Bridge, which is almost in the center of the peninsula, were 278 gals and 109 gals, respectively.

In the Shimoushigata District of Shariki Village, almost on the boundary between the Byobusan sand dune and the lowland zone, sand and water spewed out in a wide area shown in Fig. 8 during the main shock. Houses settled unevenly, drainage pipes were uplifted, electric poles and cars sank, fences moved, and the ground surface settled.

According to inhabitants of the district, the area damaged by the aftershock was almost the same as the area damaged by the main shock. Fences moved and cars sank again. However, it was impossible to compare the severity of damage caused by the

Fig. 8. Liquefaction areas in the Shimoushigata District caused by the main shock of the 1983 Nihonkai-chubu Earthquake

Fig. 9. Liquefaction areas in Tomiyachi District

Photo.2. Sand volcanoes induced in Tomiyachi District by the main and the aftershock of the 1983 Nihonkai-chubu Earthquake

two shocks because the fields and houses damaged by the main shock had not yet been repaired when the aftershock occurred.

Tomiyachi District of Shariki Village

At a narrow basin between sand dunes in the Tomiyachi District of the same village, sand volcanoes were observed during the aftershock of June 21 in an area where liquefaction had been induced by the main shock, as shown in Fig.9. Photo 2, which was taken one hour after the aftershock, shows two kinds of sand volcanoes, a dry one and a wet one, formed during the main shock and the aftershock, respectively. The volcanoes resulting from the aftershock were not large, as shown in Photo 2, but very large volcanoes, 7 m to 8 m in diameter, had been induced near the photo site by the

main shock.

Houses located at the right of the area depicted in Fig.9 were damaged by liquefaction. According to inhabitants of the district the same houses had been damaged during the Tokachi-oki Earthquake in 1968. The damage caused by the Tokachi-oki Earthquake was more severe than that caused by the main shock of Nihonkai-chubu Earthquake.

Takeda Elementary School in Nakazato Town

The aftershock also caused reliquefaction at the Takeda Elementary School in Nakazato Town. The school was built on the old bed of the Iwaki River, as shown in Fig. 10. The schoolhouses are two-story wooden structures with raft foundations, constructed in 1963.

During the main shock on May 26, the ground beneath the schoolhouses cracked in many places and spewed out sand and water, then was submerged as shown in Photo.3.

Fig.10 Liquefaction areas at Takeda Elementary School.

Fig. 10. Liquefaction areas at Takeda Elementary School

Photo.3. Sand volcanoes induced by the main shock of the 1983 Nihonkai-chubu Earthquake at Takeda Elementary School

Photo.4. Sand volcanoes induced by the aftershock of the Nihonkai-chubu Earthquake at Takeda Elementary School

The schoolhouses were severely damaged by uneven settlement, and the river dike developed big cracks. The aftershock of June 21 again caused sand and water to spew out from the ground, as shown in Photo. 4. According to some teachers, the area where sand volcanoes were observed almost coincided with the area where sand volcanoes had been caused by the main shock, as shown in Fig.10. Settlement of the schoolhouses might have increased due to the aftershock ; this is not clear, however, because the buildings had been abandoned after being damaged by the main shock.

Moreover, according to the teachers, sand volcanoes had been observed in almost the same area during the Tokachi-oki Earthquake in 1968. The damaged schoolhouses had been repaired after that earthquake.

Fig.11 shows the factors of resistance to liquefaction, F_L , at site No.4 in Fig.10, analyzed by the simplified method used by Iwasaki et al. (1978) and by Tokimatsu and

Fig. 11. Soil profile and results of liquefaction analysis at Takeda Elementary School

Yoshimi's simplified method (1983) based on SPT- N values obtained after the main shock. For these calculations, the maximum acceleration at the ground surface during the main shock and the aftershock was assumed to be 278 gals and 109 gals, respectively, based on the values recorded at the Tsugaru-ohashi Bridge, about 6 km from the school. It can be judged from Fig.11 that the medium to coarse sand layer of 2 m to 6 m depth must have been liquefied during the main shock because the F_L values of these depths are less than 1.0, as evaluated by both methods. In the case of the aftershock, the F_L values of the sand layer are more than 1.0, as evaluated by both methods. The authors cannot clarify the reason why the F_L values exceed 1.0. However, it is most probable that reliquefaction occurred in the sand layer ; this is assumed because the grain-size distributions of boiled sands taken after the two shocks coincided.

After the Nihonkai-chubu Earthquake, new reinforced concrete schoolhouses were constructed with foundations of PC piles 36 m in length, whereas the old schoolhouses had foundations of wooden piles 3 m in length.

Aomori Station in Aomori City

Aomori Station faces the sea, and the north part of the station is used as a landing

Photo.5. Damage to Aomori Station caused by the 1983 Nihonkai-chubu Earthquake

place for ferryboats. The north part is built on reclaimed land constructed around 1945, but the south part is built on natural land.

Liquefaction was induced at the north part of the station during the main shock of the Nihonkai-chubu Earthquake. Many sand volcanoes, settlement of rails and buildings, and uplift of buried tanks occurred, as shown in Photo.5. The maximum acceleration at the ground surface at Aomori Port, about 1 km north of Aomori Station, was 116 gals.

During the 1968 Tokachi-oki Earthquake, sand volcanoes and settlements of rails and buildings were observed in the same area (the Railway Technical Research Institute, 1984). The maximum acceleration at the ground surface at Aomori Port at that time was 213 gals. It can therefore be said that reliquefaction was induced by lower acceleration during the 1983 Nihonkai-chubu Earthquake.

A soil profile and factors of resistance to liquefaction, F_L , at this site are shown in

Fig. 12. Soil profile and results of liquefaction analysis at Aomori Station

Fig. 12. The F_L during the Nihonkai-chubu Earthquake and that during the Tokachi-oki Earthquake were evaluated by the Railway Technical Research Institute (1984) and by the authors, respectively, using the Iwasaki method. Based on this figure, the liquefied layer is estimated to have been about 6 meters below the ground surface during the Nihonkai-chubu Earthquake. During the Tokachi-oki Earthquake, liquefaction must have extended through a layer more than 10 m deep.

CONCLUDING REMARKS

By means of a detailed site survey of damage caused by the 1983 Nihonkai-chubu Earthquake, which occurred in northeast Japan, about ten reliquefaction sites were discovered. It is noted that reliquefaction occurred in places even when the acceleration caused by a latter earthquake was less than that caused by a former earthquake. It can therefore be said that a site liquefied by an earthquake can be reliquefied by a subsequent earthquake of the same or stronger seismic force.

If a site has experienced an earthquake, the susceptibility of the site to reliquefaction can be estimated based on investigations about liquefaction during that earthquake

by means of interviewing local residents or surveying the relevant literature. As investigations of liquefaction are easy to conduct over a wide region, this prediction method is also valid for identifying specific areas within a wide region where reliquefaction potential is greatest.

It has heretofore been thought that reliquefaction is unlikely to occur, because soil grains are believed to become more densely packed after liquefaction. However, the authors' investigation shows that reliquefaction occurs frequently. The mechanism of reliquefaction cannot be explained exactly, but the authors offer the following hypothesis :

Based on a test result using a large shaking table, Sasaki and Taniguchi (1982) reported that the upper part of a model ground remained loose, whereas the lower part became denser after liquefaction. During a similar shaking table test, the authors noticed that the upper soil of the model became like a suspension and the soil grains went into a kind of "dance" due to a strong upward stream of excess pressurized water from the lower part of the model ground and due to low overburden pressure, after liquefaction of the soil was induced. After the upward stream stopped, the "danced" soil grains settled gently. Therefore, sedimentation of the upper part of the natural ground after liquefaction seems to be the same as the original sedimentation process, caused by river action or artificial reclamation. If these sedimentation processes are almost the same, the density of the upper part of the ground may not change after liquefaction. This seems to be the reason reliquefaction can be induced. Further study is needed, however, to clarify quantitatively the mechanism of reliquefaction.

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