ZONING FOR LIQUEFACTION AND DAMAGE TO STRUCTURES DURING THE 2005 FUKUOKA-KEN SEIHO-OKI EARTHQUAKE

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ABSTRACT :

On March 20, 2005, an earthquake of magnitude 7.0, which was named as the 2005 Fukuoka-ken Seiho-oki Earthquake, occurred in the northwest part of Fukuoka City. During the earthquake, liquefaction occurred mainly in the reclaimed lands of the Hakata Bay area, resulting in structural damage. In this paper, the distribution of the sites where liquefaction occurred and the characteristics of the gradation of sand boils collected at the sites were clarified. Further, the occurrence of liquefaction in the reclaimed land was discussed with reference to some instances, and structural damages, including a flow failure of sloping ground due to liquefaction were summarized. Furthermore, liquefaction analysis was performed using a program for one-dimensional seismic response analysis and several soil profiles of the reclaimed land and alluvial ground in order to investigate the relationship between the occurrence of liquefaction and the distribution of acceleration; this was estimated from the analyses and the mechanical and physical properties of the soils.

KEYWORDS: Earthquake damage, lateral flow, liquefaction, reclaimed ground, sandy soil

1. INTRODUCTION

During the Fukuoka-ken Seiho-oki Earthquake that occurred on March 20, 2005, a liquefaction phenomenon took place mainly in the reclaimed lands of the Hakata Bay area, and damages to structures due to liquefaction were also identified. Immediately after the earthquake, a joint commission for investigating the earthquake-induced damages to structures was organized by the Kyushu branch of the Japanese Geotechnical Society and the Seibu branch of the Japan Society of Civil Engineers. This paper illustrates distinctive features of the occurrence of liquefaction, and structural damages on the basis of the results that were obtained from the site investigations, soil tests, analysis of collected data, and liquefaction analyses conducted by the joint commission.

In the site investigation, the damages to structures due to liquefaction were examined mainly in the reclaimed lands of the Hakata Bay area. Several grain-size analyses conducted using soil tests were carried out using sand boils obtained from the surface of the reclaimed lands. Data from the research and soil exploration were collected and analyzed in order to investigate the reclamation methods and materials that were used in the reclamation of several areas where liquefaction occurred during the earthquake. The liquefaction analyses were performed to investigate the relationship between the occurrence of liquefaction and the distribution of acceleration, which was estimated from the analyses and the mechanical and physical properties of the soils; further, the analyses were used to study the possibility of the occurrence of liquefaction in the reclaimed and alluvial grounds.

The results obtained from the abovementioned investigations will be presented and discussed in the following chapters.

2. EARTHQUAKE CONDITION

The outline of the Earthquake, which occurred at 10:53 a.m. on March 20, 2005 at the western offshore of Fukuoka-ken, is summarized by JMA (Japan Meteorological Agency) as follows: (1) Epicenter: the western offshore of Fukuoka-ken (N33.90 E130.20), (2) Depth: 9 km below the earth's surface, (3) Force: Magnitude of 7.0 on the Richter scale. In this paper, the earthquake is named as the 2005 Fukuoka-ken Seiho-oki Earthquake.

3. DISTRIBUTION OF SITES WHERE LIQUEFACTION OCCURRED

In a survey performed immediately after the earthquake, the occurrence of liquefaction was identified by the presence of sand boils on the ground surface. Figure 1 indicates the distribution of the sites where liquefaction occurred in the Hakata Bay area. The periods during which the reclaimed lands were constructed are also shown in Figure 1. From this figure, it can be observed that the sites that exhibited liquefaction are mainly distributed in the reclaimed lands of the Hakata Bay area and are interspersed with reclaimed lands. Therefore, the degree of severity of liquefaction due to the earthquake is not regarded to be as high as that observed in past earthquakes, for example, the 2000 Tottori-ken Seibu Earthquake (e.g. Yoshimoto et al., 2002). On the contrary, the occurrence of liquefaction in alluvial ground was almost negligible. It may be considered that the occurrence of liquefaction is related to the characteristics of earthquake motion and the magnitude of the liquefaction strength of soil, although there is a possibility that liquefaction occurred in the alluvial ground; however, sand boils did not appear onto the ground surface.

Furthermore, zoning for liquefaction was conducted by the Waterworks Bureau of Fukuoka City in 1989 when it formulated general principles regarding the mitigation of an earthquake disaster (Waterworks Bureau of Fukuoka City, 1989). In this process, the occurrence of liquefaction was evaluated using data from soil boring logs, assuming that the maximum acceleration on the ground surface was 200 gals. It was clarified that the distribution of the sites where liquefaction occurred during the earthquake corresponds with the results of the zoning for liquefaction (Seibu branch of the Japan Society of Civil Engineers, 2005).

Figure 2 shows the grain-size distribution curves of sand boils observed at several reclaimed lands in the Hakata Bay area. The particle size D_{50} is 0.15–1.06 mm and the uniformity coefficient U_c is 1.7–7.1. The boiled sand is classified as a relatively well graded middle sand to a poorly graded fine sand, provided that certain sand samples are excluded from the sand boils. Further, it was observed that the color of the sand boils was different in the reclaimed lands.

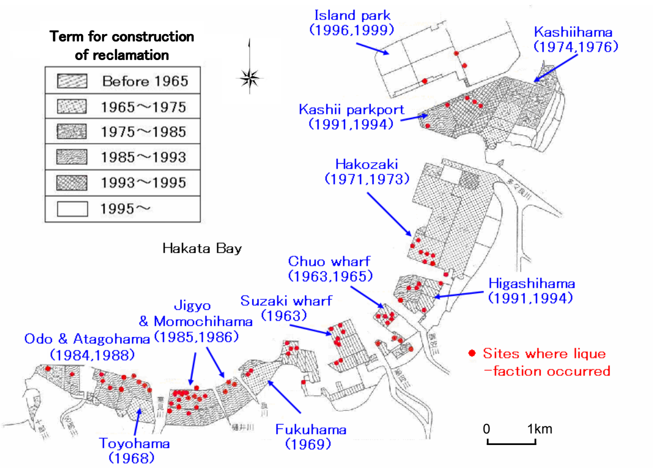


Figure 1 Distribution of sites where liquefaction occurred in the reclaimed lands of the Hakata Bay area

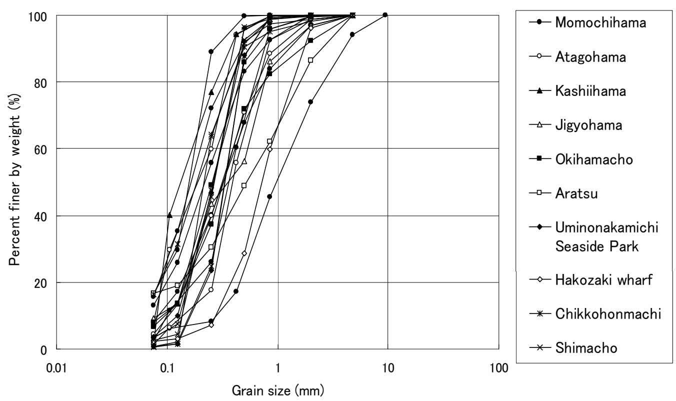


Figure 2 Grain-size distribution curves of sand boils

4. OCCURRENCE OF LIQUEFACTION IN RECLAIMED LANDS

With regard to the occurrence of liquefaction in the reclaimed lands, the following distinctive features are evident upon investigating the reclamation method and properties of the soil used for the reclamation.

1) In general, it is more difficult for liquefaction to occur if the duration of sedimentation is long. However, the trend of liquefaction resistance is not observed as shown in Figure 1. For example, although Chuo wharf and Hakata wharf were constructed almost forty years ago, heavy damages to port and harbor facilities were induced by liquefaction in the reclaimed lands. On the contrary, structures in Higashihama, Kashii Park Port, and Island City, were minimally damaged, although these reclaimed lands were constructed fairly recently, from a few years to twenty years ago.

2) In Island City, most of the land was not liquefied because dredged soil with a high proportion of fine content was used for the reclamation. However, a section of the temporary embankment of the sea wall and the backfilled ground of the quay wall were liquefied because clean sand with a small proportion of fine content was used for reclamation in these places. This phenomenon was observed in the western parts of the reclaimed lands, such as Momochihama and Atagohama.

3) In Atagohama, the lower layer and its upper layer are composed of clayey soil and sandy soil, respectively, which were soils dredged from the bottom of Hakata Bay, while the surface layer is composed of mountain sand. An exceptional phenomenon was observed in Atagohama, as shown in Photo 1. According to oral testimonies, fountain water with a volume of almost three times the inner volume of a swimming pool in elementary schools and sand boil almost three times the capacity of a 4-ton truck appeared on the ground surface. Most of the fountain water did not appear turbid. It can be considered that the phenomenon was induced by liquefaction in the sandy soil layer (Nagase et al., 2006).

4) The area in which liquefaction occurred was broader in Momochihama than in Atagohama because the reclaimed ground of Momochihama was not subjected to soil improvement. However, liquefaction was nearly absent in the residential area in Momochihama because this area was improved by the preloading method to eliminate ground subsidence.

Based on the results obtained from the abovementioned site investigations, it may be considered that individual reclaimed lands exhibited some unique liquefaction features influenced by the reclamation history, methods and materials used in the reclamation and the magnitude of the earthquake motion.

Photo 1 Location of sand boils in the residential area of Atagohama(provided by Ms. kayoko Hoshiko)

5. STRUCTURAL DAMAGE DUE TO LIQUEFACTION

During the earthquake, extensive damage occurred in port and harbor facilities and roads due to liquefaction. In addition, a huge flow phenomenon occurred due to liquefaction in the gently sloping ground in a park. In this chapter, the typical damage to the quay wall, the road and the flow failure of the sloping ground are introduced.

5.1. Damage to quay wall

In Chuo wharf, a quay wall moved around 1 m toward the sea and the backfilled ground sank by around 1.2 m. This represents the maximum extent of the damage to the quay walls. Several sand boils were observed on the surface of the backfilled ground. This quay wall is of the L-shaped concrete block type. In the groin region of the Chuo wharf area, the L-shaped type quay wall moved into the sea by around 20 cm, and several cave-ins occurred in the ground surface of the groin.

5.2 Damage to road

A road was locally uplifted in the vicinity of the intersection of Chuo road and Rinko road in Island City. The amount of uplift was approximately 1 m. In the ground of the uplift site, a buried water supply pipe with a diameter of 80 cm was raised by about 1 m. Two temporary reclamation revetments, on which embankment is sitting, are intersected and a filled sand layer with a depth of 4 m was laid as the foundation of the temporary reclamation revetment and comprised loose sand in the place. Based on the ground condition, it can be considered that the filled sand layer was liquefied during the earthquake and could not support the weight of the embankment. Moreover, it can also be considered that flow failure occurred in the liquefied sand layer, which was pushed against the area around the Chuo road, and the road near the intersection was uplifted.

5.3. Flow failure of ground due to liquefaction

At the Uminonakamichi Seaside Park, flow failure occurred in an open space with a gently sloping ground toward a pond known as "Kamo-ike." Photo 2 shows the state of the flow failure immediately after the earthquake, and Figure 3 indicates the locations at which a survey was carried out for measuring the ground displacement. Figure 4 shows the relationship between the ground displacement due to flow failure in the perpendicular direction of the waterline of the pond and its distance from the waterline of the pond. From the figure, it can be observed that the ground displacement reached a maximum of around 10 m, although the maximum displacement in the c-c line was around 1 m. It appears that a stone stairway that was constructed near the waterline had a restraining effect on the ground displacement. Further, a worker who manages tourist boats was interviewed regarding the flow phenomenon. It was clarified from this interview that the flow failure occurred almost immediately after the occurrence of liquefaction during the earthquake. The phenomenon of flow failure in this case is different from that during the 1964 Niigata Earthquake, where the flow failure supposedly occurred three minutes after the earthquake (Wakamatsu et al., 2004).

Photo 2 Flow failure of the ground at Uminonakamichi Seaside Park

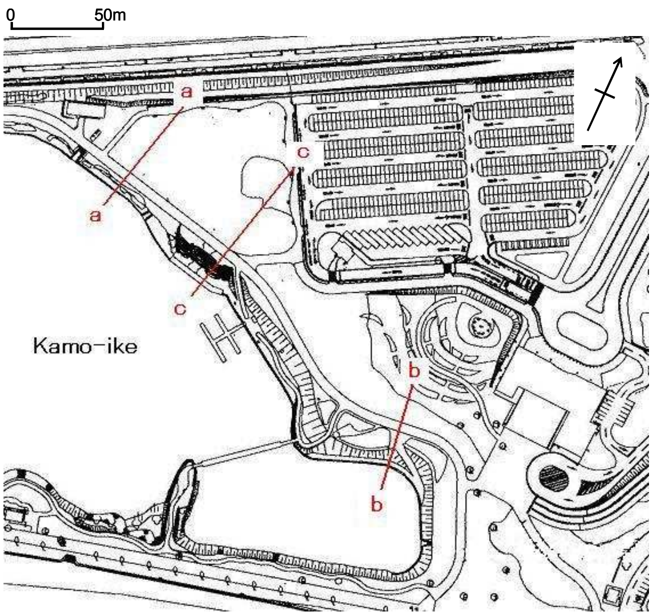


Figure 3 Locations where a survey was carried out to determine the ground displacement due to flow failure

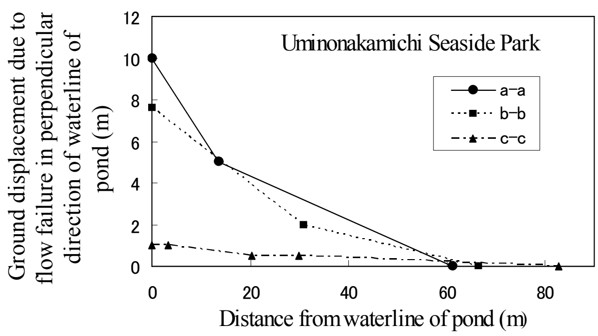


Figure 4 Relationship between ground displacement due to flow failure and distance from the waterline of the pond

6. ANALYTICAL INVESTIGATION

6.1. Analytical procedure

The sites where liquefaction occurred during the earthquake were almost restricted to the reclaimed lands. In order to clarify the reason for this peculiarity in the liquefaction phenomenon, a liquefaction analysis was performed for the reclaimed land and alluvial ground. The method of the liquefaction analysis employed by the Waterworks Bureau of Fukuoka City (1989) is explained as follows:

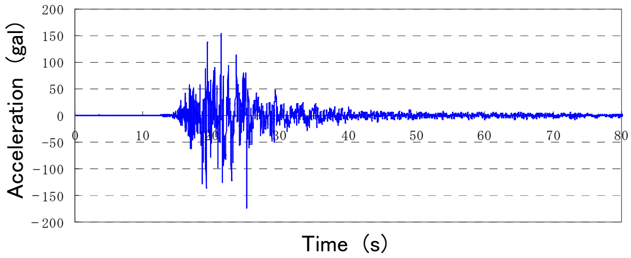


Figure 5 Wave form used for one-dimensional seismic response analysis

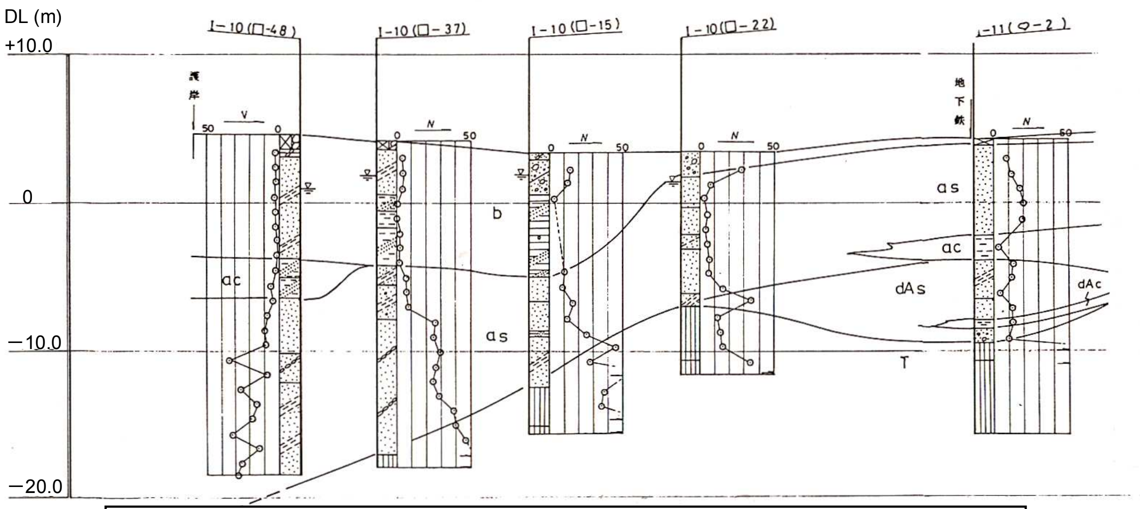
1) A program for a one-dimensional seismic response analysis, "SHAKE," was used to obtain the accelerations on the ground surface.
2) The seismic waveform for the analysis was obtained from a modification involving a conversion of the seismic record of the EW component measured on the ground surface at the Fukuoka public hall into that for the basement layer using the "SHAKE" program. Figure 5 shows the seismic waveform for the analysis. The maximum acceleration is 174.911 gal.
3) The shear wave velocity was obtained from the following empirical formulae:

$$Vs = 157\ N^{0.180} \quad \text{for clayey soil} \qquad Vs = 144\ N^{0.159} \quad \text{for sandy soil} \tag{1}$$

4) The strain dependencies of the dynamic shear modulus ratio G/G_0 and damping constant h were expressed using the empirical formulae proposed by Yasuda et al. (1985).
5) The soil boring logs used in the analysis are shown in Figure 6. This soil profile was investigated in Jigyohama by the Water Works Bureau of Fukuoka City (1988).
6) The shear stress ratio during the earthquake, L, was calculated by the following equation:

$$L = (1 - 0.015\ Z) \cdot k_{hc} \cdot \sigma_v/\sigma_v' \tag{2}$$

Z and k_{hc} denote the depth from the ground surface and the ratio of the maximum acceleration on the ground surface, which was calculated using the "SHAKE" program, to the gravity acceleration, respectively. σ_v and σ_v' denote the vertical total and effective stresses, respectively. The results obtained by the seismic response analyses using the "SHAKE" program, except for the maximum acceleration on the



b: Reclaimed ground, embankment	dAs: Diluvial sandy soil layer
as: Alluvial sandy soil layer	dAc: Diluvial clayey soil layer
ac: Alluvial clayey soil layer	T: Tertiary layer

Figure 6 Soil boring logs for liquefaction analysis

ground surface, were not used in the calculation, because it was needed to judge the occurrence of liquefaction using the simplified liquefaction analyses for practical purposes. The distribution of the maximum horizontal acceleration in the ground was relatively coincided with that evaluated by the equation (2) from the ground surface to a depth of 5 m. In the region deeper than 5 m, the maximum acceleration evaluated from the equation (2) was somewhat larger than that obtained by the seismic response analysis using the "SHAKE" program. The maximum difference between the values calculated by the two methods was a magnitude of about twenty percent of the maximum acceleration evaluated from the equation (2).

7) The liquefaction strength ratio R was calculated from two sets of equations, Methods 1 and 2, as shown in Table 1. These methods were referred to the Japanese certifications for highway bridges given by the Japan Road Association (1996, 1990). In Method 2, a value of 0.187 was added to the liquefaction strength ratio, R, on the basis of the results of Yasuda et al. (1991). This modifies that the N-value is generally underestimated because the fine content ratio is relatively high, and therefore the liquefaction strength ratio estimated by the method of the Japan Road Association (1990) is underestimated since the mean grain size is also relatively large, in Fukuoka City. Using these methods, the liquefaction ratio was obtained for the following three cases:

Case 1: Method 1 was used; the fine content ratio F_c of the silty or clayey sand and silt in the alluvial soil layer was 30% and 60%, respectively.

Case 2: Method 1 was used; the F_c-value was 40% and 80%, in the same manner as in Case 1.

Case 3: Method 2 was used; the D_{50} value of the sandy soil in the alluvial soil layer was 0.35 mm.

8) The ratio of F_L—a safety factor against liquefaction—was obtained from the following equation:

$$F_L = R/L \tag{3}$$

6.2. Results of Analysis

Figure 7 shows the results of the liquefaction analysis for Cases 1-3. The F_L-value for the reclaimed land is less than 1.0; this implies that liquefaction occurs in the reclaimed land in Cases 1-3, except in (c). However, in the alluvial soil layer, liquefaction apparently occurs for Case 1 in (a), (c), and (d), does not occur in (a) and (c), and its occurrence seems unlikely for Case 2 in (d). On the contrary, liquefaction does not occur in the alluvial soil layer in Case 3. It is evident that the result of the prediction of the occurrence of liquefaction depends on the manner in which the liquefaction strength is modified using the fine content ratio. Further for Cases 1 and 2, it may be considered that the effect of fine content on the liquefaction strength was not properly accounted for in the analysis.

Table 1 Explanation of the two sets of liquefaction strength ratios

Method 1	Method 2
$(N_a < 14)$ $R = 0.0882\sqrt{\frac{N_a}{1.7}}$ $(N_a \geq 14)$ $R = 0.0882\sqrt{\frac{N_a}{1.7}} + 1.6\times10^{-6}(N_a - 14)^{4.5}$ $N_a = c_1 N_1 + c_2$ $N_1 = \frac{1.7N}{\sigma_v' + 0.7}$ $c_1 = \begin{cases} 1 & (0\% \leq F_c < 10\%) \\ (F_c + 40)/50 & (10\% \leq F_c < 60\%) \\ F_c/20 - 1 & (60\% \leq F_c) \end{cases}$ $c_2 = \begin{cases} 0 & (0\% \leq F_c < 10\%) \\ (F_c - 10)/18 & (10\% \leq F_c) \end{cases}$	$(0.02\text{ mm} \leq D_{50} \leq 0.05\text{ mm})$ $R = 0.0882\sqrt{\frac{N}{\sigma_v' + 0.7}} + 0.19 + 0.187$ $(0.05\text{ mm} \leq D_{50} \leq 0.6\text{ mm})$ $R = 0.0882\sqrt{\frac{N}{\sigma_v' + 0.7}} + 0.225\log_{10}\left(\frac{0.35}{D_{50}}\right) + 0.187$ $(0.6\text{ mm} \leq D_{50} \leq 2.0\text{ mm})$ $R = 0.0882\sqrt{\frac{N}{\sigma_v' + 0.7}} - 0.05 + 0.187$

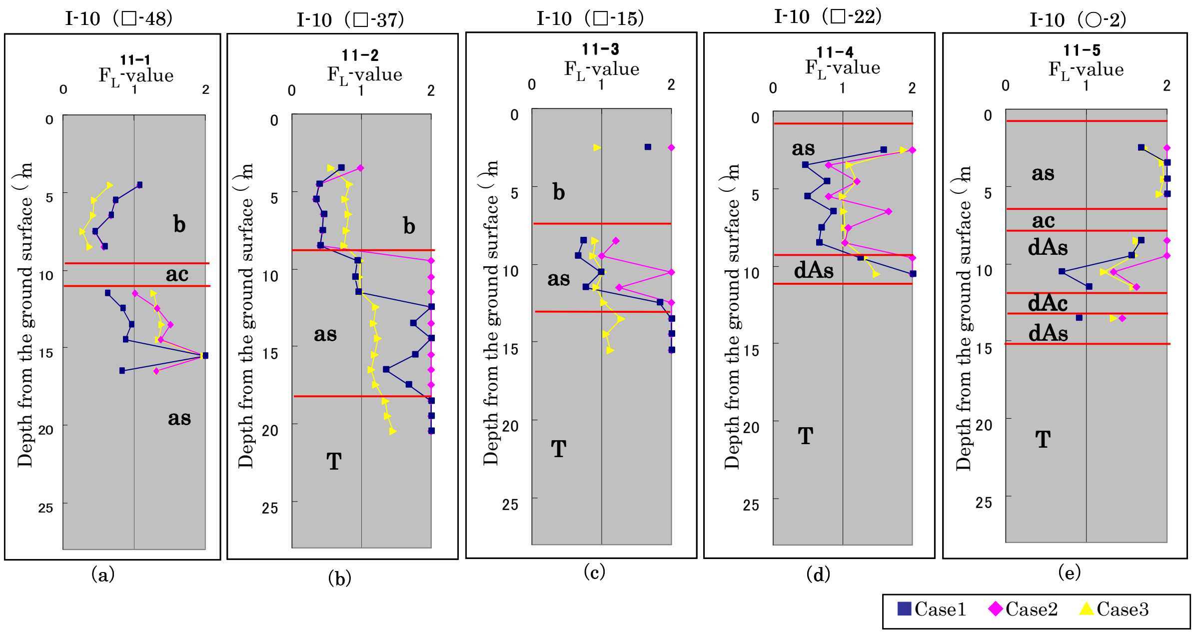


Figure 7 Results of liquefaction analysis

During the earthquake, liquefaction occurred mainly in the reclaimed ground of the Hakata Bay area and hardly occurred in the alluvial ground, described above. Therefore, it is noteworthy that the occurrence of liquefaction was suitably predicted in Case 3. It can be considered that the effect of fine content on the liquefaction strength of alluvial ground in Fukuoka City was properly estimated in Case 3, although other predictions would be necessary in this regard to confirm the accuracy of the analysis.

7. CONCLUSIONS

The 2005 Fukuoka-ken Seiho-oki Earthquake in Fukuoka City was unexpected. During the earthquake, liquefaction occurred in the reclaimed lands of the Hakata Bay area and caused structural damage, although the magnitude of the earthquake was not significantly large.

In this paper, the distribution of the sites where liquefaction occurred and the characteristics of the grain-size distribution of sand boils were discussed. In addition, the distinctive features of liquefaction phenomena in the reclaimed lands and the damages to several structures were summarized. Furthermore, the results of a liquefaction analysis were discussed in order to examine the susceptibility of the reclaimed lands and the alluvial ground of the city to the liquefaction phenomenon.

The following behaviors were observed in the investigation and study.

(1) Liquefaction occurred mainly in the reclaimed lands of the Hakata Bay area, although the occurrence of liquefaction in the alluvial ground was nearly negligible.

(2) Since the sites that exhibited liquefaction were interspersed with reclaimed lands, the degree of severity of liquefaction due to the earthquake is not regarded to be high as compared with that observed in past earthquakes, for example, the 2000 Tottori-ken Seibu earthquake.

(3) The occurrence of liquefaction in the reclaimed lands was influenced by the reclamation history and the methods and materials used in the reclamation. Further, it was observed that the sites where liquefaction occurred were often distributed along straight lines and corresponded with the locations of temporary reclamation revetments. The requirement of countermeasures against liquefaction at temporary reclamation revetments should be discussed from a seismic design viewpoint.

(4) The flow failure in Uminonakamichi Seaside Park occurred almost immediately after the occurrence of liquefaction during the earthquake.

(5) The prediction of the occurrence of liquefaction in the reclaimed lands and alluvial ground in Fukuoka City should consider the effect of fine content on the liquefaction strength.

(6) At the sites where the damage to the structures was heavy, it is necessary that countermeasures against liquefaction be applied to the ground during restoration work in order to reduce the degree of damage that might occur when an earthquake with a similar magnitude occurs in the vicinity of Fukuoka City. In residential areas such as Atagohama, countermeasures against liquefaction should be applied to the ground below the roads where the damage due to liquefaction was very severe in order to remove the anxiety among the residents of this area.

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