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ANALYSES FOR LIQUEFACTION-INDUCED GROUND FLOW DURING THE 2005 FUKUOKAKENSEIHO-OKI EARTHQUAKE

Susumu YASUDA [1], and Masatada SHIMIZU [2]

ABSTRACT

Liquefaction occurred at many sites along Hakata Bay during the 2005 Fukuokaken-seihooki earthquake. In Fukuoka City, seismic zoning for liquefaction was conducted by the authors in 1988. Then, at first, the authors compared the zoning map with the actual damage. As the results, liquefied sites were fairly coincided with estimated zone in reclaimed lands, though they were slightly different in a big sand spit named Uminonakamichi. In the sand spit, only a newly filled land was liquefied and caused liquefaction-induced flow of sloping ground. The authors took a soil sample and conducted cyclic torsional shear tests to demonstrate liquefaction and post-liquefaction behavior. Based on the results, deformation of the sloping ground was analyzed. Analyzed deformation was similar as the actual deformation

Keywords: liquefaction, seismic hazard, sandy soil, laboratory tests, analysis

INTRODUCTION

Seismicity around Fukuoka City is the lowest class in Japan. However, microzonation during earthquakes was needed because Fukuoka City is the biggest and most important city in southern Japan. Microzonation for liquefaction, strong shaking and slope failure was conducted based on several analyses by the author in 1988 (Fukuoka City Waterworks Bureau, 1988, Yasuda and Matsumura, 1991). Base acceleration for these analyses was assumed as 150 gals. According to the results of the analyses, liquefaction was predicted in almost all of the artificially reclaimed lands.

In 2005, seventeen years later, a big earthquake with a magnitude of 7.0 occurred near Fukuoka City and caused liquefaction at many sites. The maximum surface acceleration in the down town of Fukuoka was 277 gals which was almost same as the acceleration of the microzoning map. The authors conducted site investigations just after the earthquake and compared the actual liquefied sites with the zoning map.

MICROZONATION FOR SOIL LIQUEFACTION

In microzoning for liquefaction, almost 1,200 sets of borehole data were collected, and soil cross sections at the 13 areas were estimated. These sites were selected to cover the whole alluvial plain. Based on the soil cross section, it was judged that sand layers in Fukuoka City are classified into the following three layers:

[1] Professor, Civil and Environmental Engineering, Tokyo Denki University, Japan,
Email: yasuda@g.dendai.ac.jp
[2] Civil and Environmental Engineering, Graduate School of Tokyo Denki University, Japan,
Email: 06smg08@ed.ccs.dendai.ac.jp

(1) alluvial sand layer which exists in most of the alluvial plain,
(2) sand dune layer which exists along the natural coast, and
(3) artificially reclaimed sand layer.

Undisturbed samples of three sand layers were taken at the five sites and undrained cyclic triaxial tests were conducted to measure the liquefaction strength. By comparing the cyclic triaxial test results, the method of estimating liquefaction used in the specification for highway bridges (Japan Road Association, 1980) was modified. Then, liquefiable layers were predicted at all soil cross sections, by assuming a maximum surface acceleration of 200 Gals. It is necessary not only to predict the liquefiable layer but also to predict the possibility of damage to structures due to liquefaction. The possible damage was judged based on the relationship between the thickness of the liquefiable layer, H_2, and the thickness of the upper non-liquefiable layer, H_1, proposed by Ishihara (1985).

Figure 1 shows the microzoning map for liquefaction thus determined. In general, structures on artificially reclaimed land or on a part of the sand dune are susceptible to damage due to liquefaction. Liquefaction was predicted to occur in almost of the sand dune, but, damage due to liquefaction was not expected. Fill soils in artificially reclaimed lands are not unique. In general, fill soils in newly reclaimed lands are clayey soils. Therefore, it was judged that liquefaction would not occur in newly reclaimed lands. These reclaimed lands were Meino-hama, Odo, Atago-hama and Kashii-hama.

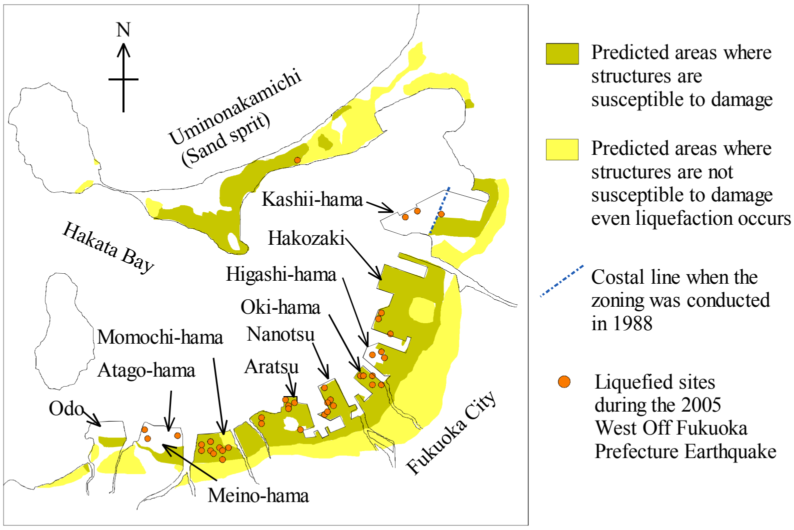

Fig.1 Hazard map for liquefaction and liquefied sites during the Fukuokaken-seiho-oki earthquake

DAMAGE TO STRUCTURES DUE TO LIQUEFACTION DURING THE 2005 FUKUOKAKENSEIHO-OKI EARTHQUAKE AND COMPARISON WITH THE PREDICTED HAZARDS

Closed circles plotted on Fig.1 show liquefied sites. Almost all sites are located in reclaimed lands along Hakata Bay. No liquefaction occurred in alluvial low land. One site in Uminonakamichi sand spit liquefied. However the liquefied site was a newly filled land on a pond. Therefore, it can be said liquefaction occurred in only artificially reclaimed lands.

Among the reclaimed lands, Oki-hama, Nanotsu, Higashi-hama Aratsu and Hakozaki, Momochi-hama were constructed before 1990. These reclaimed lands were filled mainly with sandy soil. Other reclaimed lands, Meino-hama, Odo, Atago-hama, Kashii-hama and Island City were newly filled with clayey soil. Therefore, few boiled sands were observed in the latter newly reclaimed lands. In contrast, in the former reclaimed land, liquefaction occurred at many sites. In Oki-hama, a quay wall tilted. Horizontal displacement of the quay wall was about 2 m. Two small tanks settled about 10 to 20 cm due to liquefaction in Aratsu. In Momochi-hama, sand boils were observed at many sites.

However, no damage to buildings and timber houses occurred and obvious ground subsidence did not occur at the liquefied sites. Therefore, it is estimated that liquefied layer was thin.

In Uminonakamichi sand spit, liquefaction did not occur in natural ground though some areas at the toe of sand dunes were predicted to liquefy. Borehole data were few in this sand spit because heavy structures did not exist. Therefore, in the microzoning, only two short cross sections could be estimated based on 10 boring data. Then, the ground at the toe of sand dune was judged to be liquefiable, based on the experience during past earthquakes. For example liquefaction occurred in the ground at the toe of sand dunes during the 1964 Niigata and 1983 Nihonkai-chubu earthquakes. The difference in ground conditions between the liquefied sites and at Uminonakamichi is not clear. One of the reasons may be depth of water table, because the water table at liquefied sites during past two earthquakes, was shallow. In 2005, boring data base in this area was published (Kyushu Branch of JGS, 2005). Boring data at 25 sites are existing in Uminonakamichi. The authrores tried to estimate liquefiable layer at the 25 sites. However no data along the toe of sand dune was existed as shown in Fig.2.

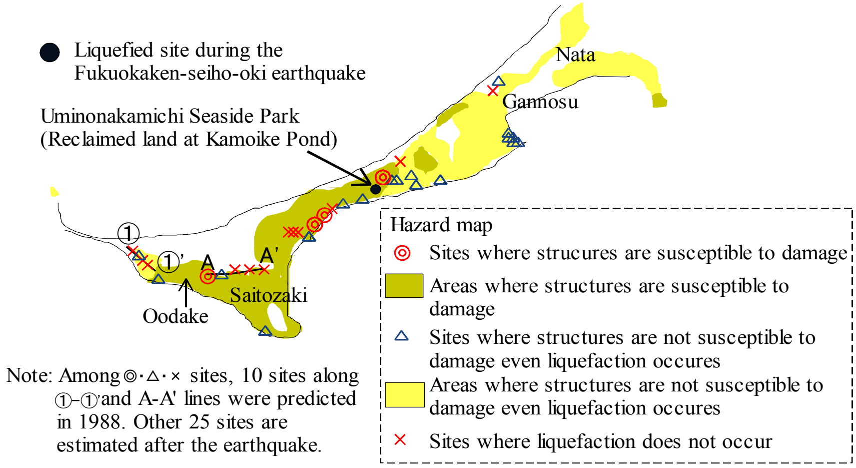

Fig.2 Hazard map for liquefaction and boring sites in Uminonakamichi sand spit

CYCLIC TORSIONAL SHEAR TESTS ON LIQUEFIED SAND AT UMINONAKAMICHI SEASIDE PARK

Photo 1 shows liquefaction at Uminonakamichi Seaside Park. This site was newly developed for a park, by filling a part of a pond with sand. Many sand volcanoes were observed in the park. Not only occurrence of liquefaction, but also liquefaction-induced ground flow occurred toward the remaining pond. The maximum horizontal displacement due to the flow was about 10 m. Flowed area extended to about 80 m behind pond shore. Many cracks were induced in parallel to pond shore. Simple piers and promenades were damaged due to the flow.

Photo.1 Liquefaction-induced flow occurred at Uminonakamichi Seaside Park

Figure 3 shows grain-size distribution curve of boiled sand. Mean diameter, fines content, maximum void ratio and minimum void ratio were 0.25 mm, 7%, 1.031 and 0.589, respectively. Cyclic torsional shear tests on the boiled sand were conducted to demonstrate liquefaction strength and post-liquefaction behavior, which was used for analyses by ALID. Figure 4 shows soil profile and SPT *N*-values, which were measured before the Fukuokakenseiho-oki earthquake. It was estimated that a fill layer, deposited to the depth of about 10 m, liquefied during the earthquake. SPT *N*-values of the fill layer were low as 3 to 6. Then, relative density for the specimen in cyclic shear tests were selected as 25 % and 45 %, based on relationships between SPT N-value and Relative density proposed by Yasuda and Nishikawa (1996) for Toyoura Sand and Gibbs and Holts (1957). One more relative density, 85 %, was also selected, to know the liquefaction strength of the sand if the fill layer is compacted to prevent liquefaction.

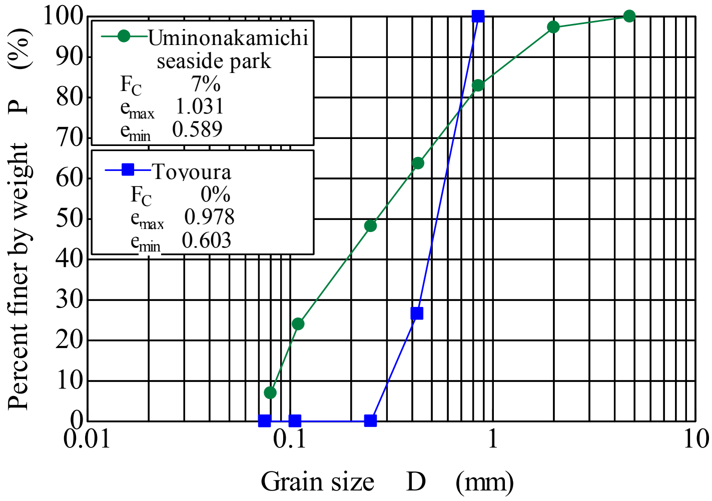

Figure 3 Grain-size distribution curves

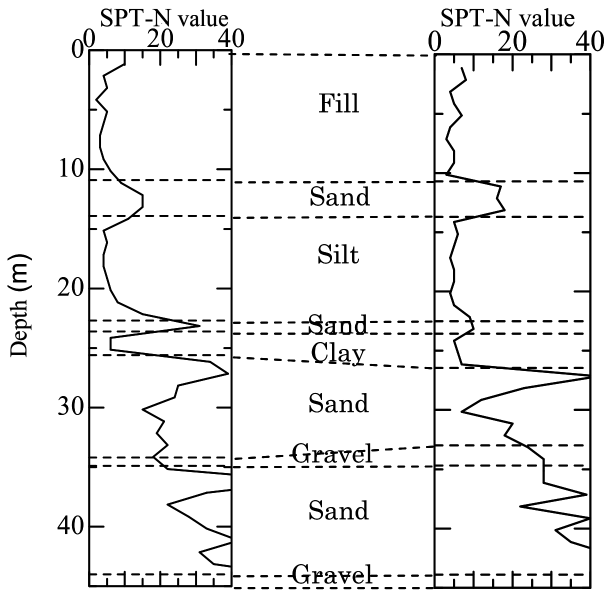

Fig.4 Soil profiles at Uminonakamichi Seaside Park

Size of a specimen for cyclic torsional shear tests was 10 cm in outer diameter, 6 cm in inner diameter, and 10 cm in height. Specimens for 45 % and 85 % of relative densities, were prepared by air-probation method. For the specimens of 25 % of relative density, a special technique was used. The sand mixed with crashed ice was poured in a mould by a spoon. Then the specimens were saturated and consolidated. Confining pressure,σ_c', was 50 kpa. After the consolidation, 20 cycles of cyclic loading at 0.1 cycles/sec. was applied to the specimens under undrained condition. Then, a monotonic loading was applied under undrained condition with a speed of 10 % of shear strain/minute. Time histories of shear stress, shear strain and pore water pressure during the monotonic loading were measured. About 4 to 8 specimens were used in one sample. Different amplitude of cyclic loading was applied to each specimen to control safety factor against liquefaction, F_L, which implies severity of liquefaction or failure. Then, relationships between cyclic stress ratio, τ_d/σ_c' and double amplitude of shear strain at 20th cycle, γ_{DA} (N=20) were plotted. And, the stress ratio to cause 7.5 % of shear strain by 20 cycles, $R_L(\gamma_{DA}=7.5\ \%, N_L=20)$ was estimated. This stress ratio is same as the stress ratio to cause liquefaction, $R_L(\varepsilon_{DA}=5\ \%, N_L=20)$ in cyclic triaxial tests.

Figure 5 shows relationships between $R_L(\gamma_{DA}=7.5\ \%, N_L=20)$ and relative density. R_L for the samples of Dr=25 % and 45 % were very small, as less than 0.1. By comparing with the R_L for Toyoura sand, shown in Fig.6 also, it can be judged that the R_L for the boiled sand at Uminonkamichi Seaside Park was smaller than that for Toyoura sand if their relative densities are same.

Time histories of shear stress during monotonic loading are shown in Fig.6. In liquefied specimen (F_L <1.0), shear strain increased with very low shear stress up to large strain. Then, after a resistance transformation point, the shear stress increased comparatively rapidly with shear strain. The shear

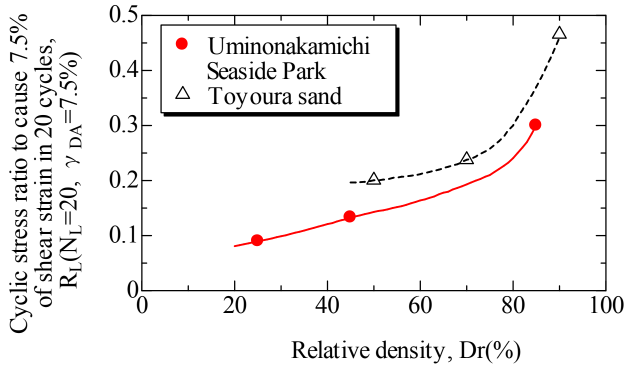

Fig.5 Relationships between relative density and cyclic stress ratio to cause liquefaction

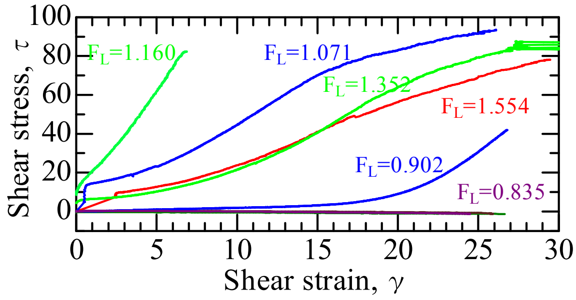

Fig.6 Stress-strain curves after cyclic loading (Dr=45%)

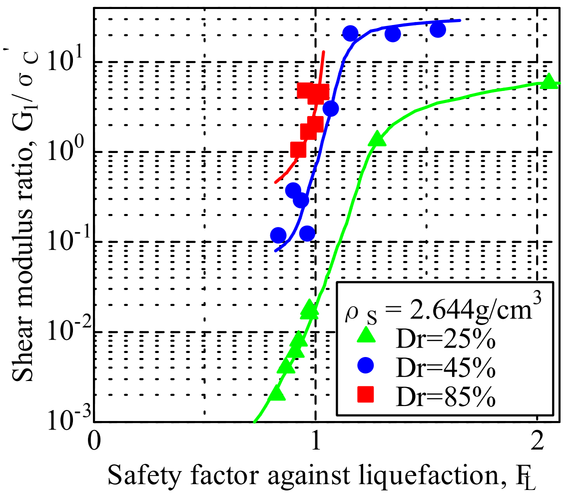

Fig.7 Relationship between G_l/σ_c' and F_L

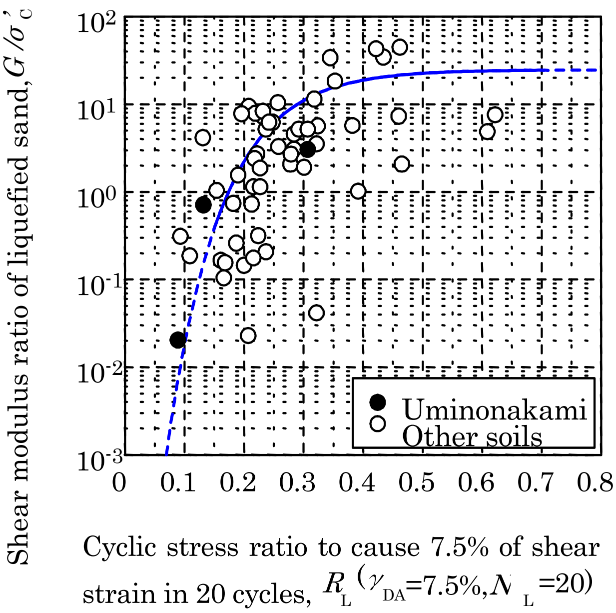

Fig.8 Relationship between G_l/σ_c' and R_L for F_L=1.0

strain up to the resistance transformation point increased with the decrease of F_L. The authors assume these curves by a bilinear model with G_1, G_2 and γ_L (Yasuda et al., 1999). The G_l means shear modulus of a liquefied soil. Figure 7 shows the relationships between G_l/σ_c', Dr and F_L. G_l/σ_c' decreased with a decrease of F_L and Dr. The authors proposed the relationship between G_l/σ_c', $R_L(\gamma_{DA}=7.5\ \%, N_L=20)$ and F_L as shown in Fig.8 (Yasuda et al.(2004)). Closed circles show the data of the boiled sand. These data are almost on the proposed curve. And G_l/σ_c' of Dr=25 % is the lowest compared with other soils.

ANALYSES FOR LIQUEFACTION-INDUCED FLOW

The liquefaction-induced flow, occurred at Uminonakamichi Seaside Park, was analyzed based the test results. Computer code used for the analyses was ALID/Win, which is a static analytical program considering the decrease of shear modulus due to liquefaction (Yasuda et al., 1999). The cross section analysed is shown in Fig.9. Length and depth of the cross section were 168.7 m and 39.8 m,

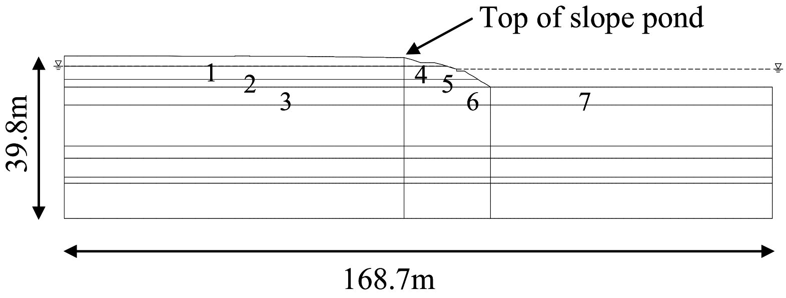

Fig.9 Model for analyses at Uminonakamichi Seaside Park

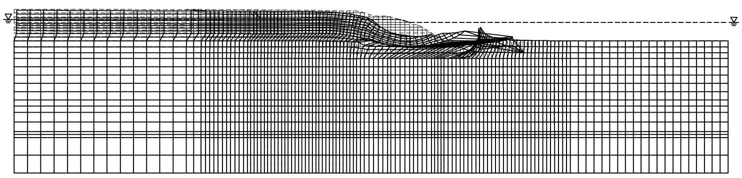

Fig.10 Analyzed deformation

respectively. Soil layers were judged from the boring data shown in Fig.4. Brocks from No.1 to No.7 are estimated liquefied zones. The blocks below these liquefied blocks are not liquefied zones.

Relative densities of liquefied blocks were estimated based on SPT *N*-values. Then liquefaction strength, R_L, was estimated by using the relationship shown in Fig.5. Shear stress induced in the ground was estimated based on the simplified equation introduced in the specification for highway bridges (Japan Road Association, 1980). Various maximum ground surface acceleration from 90 Gals to 300 Gals were assumued in the estimation. Then the distibution of safety factor agaist liquefaction, $F_{L,}$ was estimated. Elastic moduli of soils before earthquake, E, were estimated from SPT *N*-values by the formula E=2800N (kN/m^2). Shear moduli of liquefied soils were evaluated from Fig.7. Reduction of shear moduli of not liquefied soils due to earthquake were assumed as 1/40.

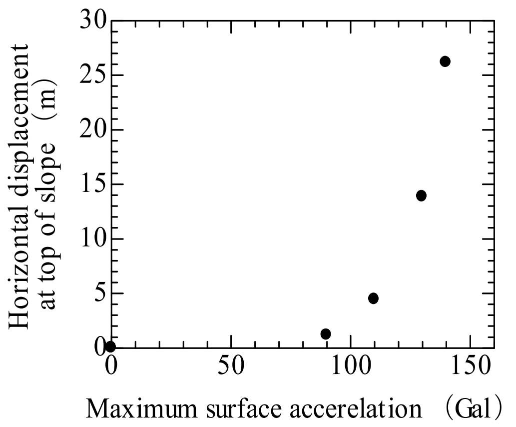

Fig.11 Relationship between maximum surface acceleration and horizontal displacement at top of slope

Figure 10 shows the analysed deformation at 110 Gals of the maximum ground surface acceleration. Liquefied ground flowed towards the pond. Horizontal displacement at the top of slope was about 5 m. The displacement was similar as the actual displacement. Figure 11 shows the relationship between the maximum surface acceleration and analysed horizontal dispacement at the top of slope. The horizonatal displacement increased with the maximun surface acceleration. Especially, the horizontal displacement increased drastically when the maximum surface exceeds about 150 Gals. This means the liquefacted soils are very loose, and the soil is apt to sudden drop of shear modulus and causes very large deformation, once liquefaction occurs.

The maximum surface acceleration at Uminonakamichi Seaside Park is not clear because there were no seismic record near the site. However, it may be less than 270 Gals, which was recorded in downtown of Fukuoka City, because the ground here is not soft.

CONCLUSIONS

In Fukuoka City, microzonation for liquefaction was conducted based on several tests and analyses in 1988. Liquefaction was predicted in almost all of the artificially reclaimed lands. Seventeen years after the microzonation, the Fukuokakenseiho-oki earthquake hit Fukuoka City. Liquefaction occuuers at many sites. Liquefied areas were fairly coincided with the predicted areas. However liquefaction did not occure in natural groud behind sand dune in Umononakamichi sand spit, which had been judged as liquefiable zone. One site, filled in a pond, in Uminonakamichi, liquefied and caused ground flow toward a pond. Deformation of the ground was analyzed by a code named ALID/Win. Actual deformation could be explained by the analyses.

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