CHARACTERISTICS OF LIQUEFIED SANDS DURING MINO-OWARI, TOHNANKAI AND FUKUI EARTHQUAKES

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ABSTRACT

This paper presents the results of field investigations at the places where sand volcanoes were formed and eruption of water and soil was observed during Mino-Owari, Tohnankai and Fukui earthquakes. The soil strata which were presumed to have liquefied were identified on the basis of previous studies and compared with the observed phenomena during the earthquakes. The results indicate that the eruption of water and soil during the earthquakes was not necessarily associated with a complete liquefaction of sand of the type observed during the Niigata earthquake of 1964. The Seismic intensities during the earthquakes were from V to VI according to the Japanese Meteorological Agency Intensity Scale, and most of the liquefaction of the saturated sand occurred under the following conditions: The soil was coarse grained in accordance with the unified classification system, having the 50% size of less than 2.0 mm and the uniformity coefficient of less than 10. The effective overburden pressure was less than 2.0 kg./cm², the relative density was less than 75% and no fine grained soil strata lay above the saturated sand. Also presented are microscopic photographs of sands which are presumed to have liquefied.

1. INTRODUCTION

During earthquakes, sand volcanoes and eruption of water and soil from the ground are often observed, and especially in the Niigata earthquake of June 16, 1964, extensive damage to structures occurred as a result of a decrease in bearing capacity of the soil. The decrease of bearing capacity of the soil during earthquakes is due to two phenomena, one of which is a liquefaction of the soil from the ground surface to some depth and the other is the loosening of the soil due to the upward flow of water which resulted from liquefaction of the soil at some distance below the ground surface.

Many experiments on the liquefaction of saturated sands are carried out by vibrating sand boxes. Florin and Ivanov (1961) and Yoshimi (1967) show-

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ed that the presence of a surcharge on the surface of the sands affected the mechanism of the liquefaction. Lee and Seed (1967) in their cyclic triaxial tests and Yoshimi (1967) showed that the liquefied state consisted of different stages. Seed and Lee (1966) concluded on the basis of their test results that the void ratio of the sand, the confining pressure acting on the sand, the magnitude of the cyclic stress or strain and the number of stress cycles to which the sand was subjected determined the danger of liquefaction of a saturated sand.

Detailed case histories of sand volcanoes and eruption of water and soil during earthquakes are found for Mino-Owari and Tohnankai earthquakes (Yokoo et al., 1965; Kotoda et al., 1967), Kanto earthquake (Odera, 1964), Fukui earthquake (Geographical Survey Institute, 1949), Niigata earthquake (Ohsaki, 1966; Koizumi, 1966; Kishida; 1966), Madrid earthquake (Fuller, 1912), Bihar-Nepal earthquake (1939) and for Jaltipan earthquake (Marsal, 1961).

The author carried out field investigations on the basis of the papers on Mino-Owari earthquake, Tohnankai earthquake and Fukui earthquake. Borings were made at the places where sand volcanoes, eruption of water and soil occurred. Borings were also made for comparison at the places where such phenomena were not observed. Standard penetration tests were carried out in the field and specific gravity, grain size distribution and consistency limits of the soil samples were determined in the laboratory. Microscopic photographs of soil particles were also taken. The author attempted to identify the liquefied zone of the soil on the basis of the previous research and checked the results with the case histories.

2. SOIL EXPLORATION AND DAMAGE TO THE GROUND CAUSED BY THE EARTHQUAKES

2-1. *Mino-Owari earthquake (1891)*

Mino-Owari earthquake of October 28, 1891, was a shock of magnitude about 8.4 on the Kawasumi scale, with its epicenter located some 30 km. north of Gifu city. The locations of the places investigated are shown in

Fig. 1. Location of Borings (Mino-Owari Earthquake)

GRAVEL
 SAND
 SILT
 CLAY

(I) ŌGAKI CITY BANGOKU TOWN

Fig. 2-I

GRAVEL
 SAND
 SILT
 CLAY

(II) GINAN WEST PRIMARY SCHOOL

Fig. 2-II

SOILS AND FOUNDATIONS

GRAVEL SAND SILT CLAY

(III) UNUMA TOWN

Fig. 2-III

GRAVEL SAND SILT CLAY

(IV) OGASE POND

Fig. 2-IV

Fig. 2. The Results of Soil Exploration
(Mino-Owari Earthquake)

Fig. 1, and the result of the soil exploration are shown in Fig. 2. Fig. 2-(I) indicates the soil profile of the place where eruption of water and soil was observed. This area was in an artesian condition and artesian wells were used until 1940. It is not clear whether the eruption of water resulted from a liquefied condition or from the artesian condition. Fig. 2-(II) shows the soil profile of the playground of a primary school where many sand volcanoes occurred during Mino-Owari and Tohnankai earthquakes. Figs. 2-(III) and (IV) show the soil profiles of the places where cracks were found and white mixture of water and soil came out from the ground. These two places are located near small hills and these areas might be in an artesian condition.

Fig. 3. Location of Borings (Tohnankai Earthquake)

GRAVEL SAND SILT CLAY

(I) KOMEI TOWN

Fig. 4-I

SOILS AND FOUNDATIONS

GRAVEL SAND SILT CLAY

(II) MEIKO STREET

Fig. 4-II

GRAVEL SAND SILT CLAY

(III) IENAGA SHINDEN

Fig. 4-III

Fig. 4. The Results of Soil Exploration
(Tohnankai Earthquake)

2-2. Tohnankai earthquake (1944)

Tohnankai earthquake of December 7, 1944 was a shock of magnitude about 8.3 on the Gutenberg-Richter scale, with its epicenter located some 165 kilometers south-southwest of Nagoya city. The author carried out the field investigation on the basis of the paper by Yokoo et al. (1965) as in Fig. 3. The results of the soil exploration can be seen in Fig. 4. Fig. 4-(I) shows the soil profile of the place where subsidence of the ground and extensive damage to houses occurred as a result of liquefaction of the sand. A buddhist temple which was supported on piles did not show any settlement, but the ground around the temple subsided about 40 cm and water erupted during the earthquake. The tip of the piles were at depth of about 8.00 meters below the ground surface. Fig. 4-(II) shows the soil profile of the place where very fine soil come out from the ground, and houses settled as much as about 1.00 meter. Fig. 4-(III) shows the soil profiles where differential settlement of houses occurred as a result of eruption of water and sand.

2-3. Fukui earthquake (1948)

The Fukui earthquake of June 28, 1948 was a shock of magnitude 7.2 on the Gutenberg-Richter scale, with its epicenter located some 5.0 kilometers

Fig. 5. Location of Borings (Fukui Earthquake)

east of Fukui city. Geographical Survey Institute of the Ministry of Construction took aerial photographs of the ground soon after the earthquake, and published a detailed case history of the damage to the ground. The author carried out the field investigation on the site selected on the basis of the report by Geographical Survey Institute (1949) as shown in Fig. 5. Most of the sand volcanoes were located in two regions, one of which was a region along the Kuzuryu river (Fig. 5) and the other a region away from the Kuzuryu river. Along the Kuzuryu river, the author selected two places for investigation. Fig. 6-(I) shows a soil profile of a place where sand volcanoes were recognized, and Fig. 6-(II) shows the soil profile of a place where no eruption of water and sand volcanoes were found. The distance between these two places are about 500 m. The place shown in Fig. 6-(I) is a paddy field where drains rapidly when the irrigation pump stops. The place shown in Fig. 6-(II) is an old village where the ground level is about 1.00 m. higher than the surrounding paddy field. The distributions of the

GRAVEL SAND SILT CLAY

(I) TAKAYA TOWN 45-35

Fig. 6-I

Fig. 6-II

GRAVEL
 SAND
 SILT
 CLAY

(II) TAKAYA TOWN 2-168

Fig. 6-III

GRAVEL
 SAND
 SILT
 CLAY

(III) SHONENJI TEMPLE

(IV) AGRICULTURAL UNION

Fig. 6-IV

Fig. 6. The Results of Soil Exploration (Fukui Earthquake)

sand volcanoes near these two places are approximately parallel with the Kuzuryu river. The sand volcanoes near Maruoka town (Fig. 5), however, are distributed randomly. Fig. 6-(III) shows the soil profiles of a temple site, where the eruption of water and sand volcanoes were quite prominent, and the main building of the temple settled 0.30 m. as a result of the liquefaction of the sands. The distance between the places of Fig. 6-(III) and Fig. 6-(IV) is about 500 m. The place of Fig. 6-(IV) showed no eruption of water and sand volcanoes. Fig. 6-(IV) is located in the center of an old village, the ground level of which is a little higher than the surrounding paddy field. Much of the eruption of water and sand volcanoes were found in the surrounding paddy field and also at the temple site, but no eruption of water and sand volcanoes were found in the old village.

3. ANALYSIS OF THE RESULTS OF THE INVESTIGATION

As indicated by Seed and Lee (1967), the void ratio of the sand, the confining pressure acting on the sand, the magnitude of the cyclic stress or strain and the number of stress cycles to which the sand is subjected determined the danger of liquefaction of a saturated sand.

The magnitude of the confining pressure acting on the sand is an important factor. Florin (1961) stated that the saturated soil which was placed at a depth of more than 15 m. below the ground surface was hardly lique-

fied. Ohsaki (1966) showed in his report on damage to reinforced concrete buildings in Niigata that the upper surface of the liquefied soil layer in the most severely damaged area is mostly situated at a depth of less than 8 m. below the ground surface. Koizumi (1966) estimated in his report that on the basis of standard penetration test results the soils at depths of 20 to 25 m. below the ground surface were liquefied during the Niigata earthquake. The author estimated the effective overburden pressure of the liquefied soil during the Niigata earthquake to be approximately 0.8 to 1.8 kg/cm². According to Seed and Idriss (1967), the number of significant cyclic shear stresses was about 10 and the shear stress at a depth of 15 m. was about 0.2 kg/cm² during the Niigata earthquake. When the initial horizontal stress in the ground in Niigata is the same as the earth pressure at rest, the effective confining pressure at a depth of 15 m. is less than about 1.0 kg/cm². Lee and Seed (1967) in their cyclic triaxial tests showed that at low confining pressures, on the order of 1.0 kg/cm², regardless of the density of the sand, large strain amplitudes might develop under undrained cyclic loading conditions when the cyclic stress was only 5% of that causing failure under the static undrained loading conditions. Peacock and Seed (1968) showed in their simple shear tests that the vertical confining pressure of 2.0 kg/cm² caused liquefaction of a saturated sand at a relative density of 80% in 10 cyclic shear stresses, the peak value of which was about 0.2 kg/cm². From the above-mentioned field observations in Niigata and cyclic triaxial and simple shear test results, the author assumes that a saturated sandy soil is not likely to liquefy if the value of effective overburden pressure exceeds 2.0 kg/cm². The number and amount of cyclic shear stresses in Mino-Owari, Tohnankai and Fukui earthquakes are not equal to those during the Niigata earthquake, but the author adopted the above mentioned stress condition in his analysis.

The relative density of sands is usually estimated indirectly by empirical relationships between standard penetration test results (N values) and effective overburden pressures. This relationship was first studied by Gibbs and Holz (1957), but the grain size distributions of sands, the diameter and shape of sand particles and the water content of sand affect this relationship. Fujita (1968) summarized the previous data of this relationship and the author arranged this relationship for the value of effective overburden pressure of 0, 1.0 kg/cm² and 2.0 kg/cm² as shown in Fig. 7. Lee and Seed (1967) in their cyclic triaxial tests showed that at relative densities below approximately 50%, initial liquefaction and complete liquefaction occurred almost simultaneously; however, at relative densities above approximately 70%, a considerable number of stress cycles was required to develop large strains. Peacock and Seed (1968) showed in their simple shear tests that the

Fig. 7. Relationship Among Relative Density of Sands, Standard Penetration Test Results, and Effective Overburden Pressure

behaviour of the sand with a relative density below 80% is quite different from the behavior of the sand with a relative density above 80% and that a small increase in relative density above 80% resulted in a substantial increase in the cyclic stress required to cause initial liquefaction or failure in a given number of cycles. The author assumes that a saturated sandy soil is not likely to liquefy if the relative density exceeds 75%.

Fig. 8 shows the relationship between the standard penetration test results

Fig. 8. Probability of Liquefaction of Saturated Sand

and the effective overburden pressure in the case of the relative density of 75%. This relationship was compared with the relationship between depth of foundation, penetration resistance and extent of damage in the Niigata earthquake (Kishida, 1966) and also with the relationship between the depth of penetration tests and the observed critical penetration resistance by which the liquefied sand stratum in the Niigata earthquake was identified (Koizumi, 1966). These relationships show a fairly good agreement with the proposed assumption that a saturated sandy soil is not likely to liquefy if the relative density exceeds 75%. At the places investigated, the relative densities were estimated from the standard penetration tests. The density of sands tends to increase during a strong earthquake as indicated by cyclic shear tests by Seed and Lee (1966). In this investigation, however, the relative densities are estimated on the basis of field data obtained after the earthquakes.

Murphy (1960) indicates in his shaking table tests on sand in a box, that the sand with more than 10% of silt and clay content is hardly liquefied. But other investigation (Bihar-Nepal earthquake, 1939; Marsal, 1961) showed that a soil which contains a considerable amount of silt may liquefy during earthquakes. The author classified the soil samples into fine grained soil and coarse grained soil in accordance with the unified classification system of soils (1952) in which the coarse grained soil has a 50% size greater than 0.074 mm and the fine grained soil has a 50% size equal to or smaller than 0.074 mm. The values of 50% size of the soils of which the relative density is estimated below 75% and of which the effective overburden pressure is less than 2.0 kg/cm^2 are plotted against the uniformity coefficient of the soils as shown in Fig. 9. The soils with uniformity coefficients more than 100 are plotted at the uniformity coefficient of 100. The coarse grained soil which is located adjacent to a fine grained soil strata (marked Δ) or which is located between two fine grained soil strata (marked $\times$) shows higher values of the uniformity coefficient than the coarse grained soil which is sandwiched between the coarse grained soil strata (marked $\bullet$). Most of the black circles in Fig. 9

Fig. 9. The Classification of the Soil

are within the range of $D_{50} < 2.0\text{mm}$ and $U_c < 10$. The author assumed that the effective overburden pressure less than 2.0 kg/cm^2 , the relative density below 75% and saturated coarse grained soil in accordance with $0.074\text{ mm} < D_{50} < 2.0\text{ mm}$ and $U_c < 10$ determined the occurrence of liquefaction during the earthquakes of intensity V to VI according to the Japanese Meteorological Agency Intensity Scale. The author classified the observed phenomena into three cases. (1) complete liquefaction at the ground surface, (2) eruption of water and soil, and (3) no such phenomena. The complete liquefaction at the ground surface was associated with many sand volcanoes and/or ground subsidence with eruption of water during earthquakes. The eruption of water and soil means that mixture of water and soil erupted during the earthquakes without clear evidence of sand volcanoes. The soil profiles investigated were evaluated on the basis of the author's criteria to identify the zones which presumably liquefied as shown in Fig. 10. The soil profiles in Fig. 10-(I) contain liquefied zones from near the ground surface to some depths. The soil profiles in Fig. 10-(II) and 10-(III) also contain liquefied zones except at one place, but the soil near the ground surface are not affected. Differential settlement of houses occurred at the place of Fig. 4-(III) which belongs to the case of Fig. 10-(II).

Fig. 10. Soil Profiles Showing Liquefied Zones

(2) Diameter $< 0.84^{mm}$ Ginan West Primary School
(Ref. Fig. 2(II)) Depth 10.55~16.50 meter

(4) $0.105^{mm} \leq$ Diameter $< 0.25^{mm}$ Shonenji Temple
(Ref. Fig. 6(III)) Depth 0.00~1.20 meter

(1) Diameter $< 0.42^{mm}$ Ogaki City (Ref. Fig. 2(I))
Depth 13.20~17.95 meter

(3) Diameter $< 0.42^{mm}$ Komei Town (Ref. Fig. 4(I))
Depth 2.80~4.10 meter

Fig. 11. Microscopic Photographs of Sands Presumably Liquefied and Grain Size Distribution Curves of These sands

(5) Diameter $< 0.42\text{mm}$ Shonenji Temple (Ref. Fig. 6(III))
Depth 1.80~3.60 meter

(6) Diameter $< 0.84\text{mm}$ Agricultural Union (Ref. Fig. 6(IV))
Depth 4.10~5.20 meter

(7) Grain Size Distribution Curves

Fig. 11. Microscopic Photographs of Sands Presumably Liquefied and Grain Size Distribution Curves of These sands

It is not clear whether or not the liquefaction of a deep soil stratum caused the differential settlement.

Microscopic photographs of the sand which had presumably liquefied were taken to investigate the shape of sand particles as shown in Fig. 11. No distinctive characteristics of the shape are recognized in the liquefied sands, but it can be seen that the shapes of the sand particles are fairly angular and that quartz is present frequently.

4. CONCLUSIONS

1. The eruption of water and soil during earthquakes was not necessarily associated with a complete liquefaction of sand of the type observed during the Niigata earthquake of 1964.

2. The criteria assumed by the author to identify saturated sands which had presumably liquefied during three earthquakes of intensity V to VI according to the Japanese Meteorological Agency Scale seem to offer a plausible explanation of the observed phenomena such as complete liquefaction at the ground surface and eruption of water and soil.

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NOTATION

- D_{10} : 10% size of the soil particle
- D_{50} : 50% size of the soil particle
- D_{60} : 60% size of the soil particle
- Dr : Relative Density
- N : Number of blows in Standard Penetration Test
- U_c : Uniformity Coefficient

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