Re-consideration of liquefaction phenomena

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ABSTRACT

This paper aims to re-define a liquefaction phenomenon, and to discuss their mechanism. After a short history regarding to liquefaction events in Japan had been reviewed, then, repeatability, selectivity, and time-delay properties of liquefaction , which are named in this paper, are re-defined based on records of archaeological investigation from relict sites in Tokushima, Japan. In order to discuss those mechanisms of liquefaction properties, series of cyclic shear tests under CU and CD conditions were performed. It was found that shrinkage phenomenon by cyclic shear, basically, comes from a phenomenon of homogenization of a sample. Authors tried to explain the phenomena of the liquefaction based on mechanisms which were observed from cyclic tests.

Keywords: liquefaction, shear stress, effective stress, displacement

1 INTRODUCTION

In Japan, a term of liquefaction was used by T. Mogami in 1953 in a report on damage from the Showa-Nankaido earthquake (1946, M=8.0, at reclaimed land, Hyogo prefecture).

It was after the event of the Niigata earthquake (1964, M7.5) when a word 'liquefaction' became to be known and used widely. In the report of Japanese Society of Civil Engineering (1964), several sand boiling measuring over 6m in height were recorded and many sand craters measuring over 2m in diameter appeared on the ground just after the event with large horizontal displacements of land measuring several meters due to liquefaction. It was recorded that the number of destroyed houses in the city was counted to be over 2,000. Two thirds of which were estimated to be damaged due to liquefaction, though the maximum horizontal acceleration of the earthquake was around 160gal, which was not an extremely large acceleration from a sense of today.

Most of damages related to liquefaction due to earthquakes in Japan has been reported up to the present date. Such as, Noshiro City, Akita prefecture, was struck by the Nipponkai-chubu earthquake (1983, M7.7). Over 1,500 houses were destroyed due to liquefaction from the earthquake, which was the second largest number of records of damages in Japan. Kushiro City, in Hokkaido has been known as an area in Japan to suffer from many earthquakes.

In 1995 the Hyogo-Nanbu earthquake struck an area of Kobe city (M=7.3, referred as Kobe earthquake in this paper). Kobe-port Island, which was reclaimed with well graded sand and gravels from a near mountain side, suffered severe damage of liquefaction. Before the experiments of liquefaction damage, it was considered that the area was strong enough against liquefaction due to earthquakes. However, the island showed liquefaction damage of settlement measuring over 50cm in a large area. This observation shatters our common knowledge of liquefaction that to use well graded materials for reclamation prevent from damage of liquefaction. Many pier walls at Kobe-port island showed displacement to outside from the pier axis measuring 2 to 3m (the maximum displacement was 4.4m) due to liquefaction.

Whereas, some of them had no damage from the earthquake as they were sufficiently rein-forced to prevent earthquake damage, which were designed using a high standard of K_H=0.25 (normally K_H=0.18 is used). It was also observed at Kobe-port Island that there was a clear inverse-linear relationships of settlement to N-value intensity of SPT. These observations proved the effect of countermeasure techniques against liquefaction damage.

2 TRACES OF LIQUEFACTION OBSERVED AT RELICT SITES

Normally a crater with a sand mound has been observed on a ground surface has been observed as a trace of liquefaction. However, chained lines of sand ejection were observed at several liquefaction traces, which are considered as "a true mode of sand ejection", though a sand crater was introduced as a trace of liquefaction.

The authors became interested in properties of liquefaction from investigation reports of relict sites in Tokushima. In Japan, a research field of archeology of paleo-earthquake was initiated by Sangawa (1992), who pointed out several new views about liquefaction phenomena. The sketch shown in Fig.1 is a cross section from a relict site, Miyanomae, Tokushima, which shows that liquefaction happened several times at the same location, which is referred as a mode of repeatability of liquefaction in this paper.

Fig.2 is a photo of a relict site of Hariehama, Shiga Prefecture, which proved that liquefaction can occur even in a gravel layer. It shows that only sand was sorted to be an ejected mound of liquefaction through a blow-out hole, which caused to make misunderstand that only sand layers suffered liquefaction damage.

Table 1 shows main issues of investigation records at an each relict site in Tokushima Prefecture, locations of which are shown in Fig. 3. Number of km in the first column of the table shows distance from mouth of the river Yoshino (see Fig.3). A sketch of a relict site of Miyanomae (No.1 in Fig. 1) was investigated and found to have had four instances of liquefaction which related with four events of Nankai-trough earthquakes. This record shows repeatability of liquefaction at the same site, which suggests that a place where liquefaction occurs once should be the first candidate of a place to take precautions against liquefaction damage.

An interesting record of a re-liquefied phenomenon just after the Kobe-earthquake was witnessed that small upheaval tumors were observed from places of old liquefaction traces at a relict site of Kurotanigawa-guntou (No.5 in Table 1) when the site being investigated. The same phenomena with a small sand re-ejection was observed at a relict site of Ohgaki (No.13) at a distance of 68 km far from the mouse of the river Yoshino, though liquefaction phenomena was thought to be observed in an area of soft ground near seashore before the record.

Wakamatsu (1991) summarized liquefaction records from 128 sites in Japan and found that re-erupted sand mounds of liquefaction were detected at 40 locations in them, which supports a concept of the repeatability of liquefaction. It suggests that these facts proved increase of density of liquefied layer being limited.

It should be noted that the same combination of lique-faction events have not happened through all recorded years at these relict sites. And, trace of liquefaction at Kurokawa-guntou (No.5), Kawabata (No.6) and Shikichi (No.3) were developed before 900 years ago, though several huge earthquake events occurred in the period of recent 900 years, with no special feature of land conditions of liquefaction. The properties of phenomena are named as a mode of selectivity of liquefaction.

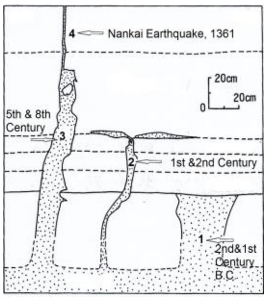


Fig. 1. Miyanomae relict site, Kurotani-gawa, Tokushima (Sangawa, 1992)

Fig.2. Trace of liquefaction at Harie-hama relict site, Shiga (Sangawa,1992)

Table 1. Record of relict sites of liquefaction Tokushima

No.	Site or town, km*	Comments (era/year of event, records of liquefaction or damages from events, etc.)
1	Miyanomae, Itano, 15km	Meiou (Muromachi era/1498± ?), Shouwa era/1946 : Sand ejection were observed (L200×W1.5cm)
2	Kurotani-Kojyo, Kamiita,14km	Kohun-era (beginning of the 3rd century?), Muromachi era (14th century) and Keicho, Edo era (1605)
3	Kojyo-B, Itano, 5km	Meiou (Muromachi-era/1498± ?), Ansei (Edo era/1854): Width of sand ejection was measuring 15 cm
4	Kurotani-gawa, -Miyano-mae, Itano,15km	Late Yayoi era (the 1st to 2nd century), Muromachi era/1361, Keichou (Edo era/ 1605) : sand ejection of liquefaction were found (see Fig.2). Length of a sand ejection was measuring 20m, and the direction was measured from SE to NE.
5	Kurotanigawa-Gunto, Itano, 14km	Late Yayoi (the 1st to 2nd century), Hakuou (Aska era/684) : parallel traces of sand ejection from WNW to ESE were found (length: over 100cm, width: 5～7cm.
6	Kawabata, Itano, 14km	Nara era/887?, Those traces of lique-faction appeared at the event of Ninna quake or more old earthquake.
7	Shoukiji, Aizumi, 9km	Houei-Nankai (Edo era/1707), two sand ejection holes were found.
8	Naka-Shimada, Tokushma,8km	Shouhei (Heian era/1361, Meiou (Heian/ 1498± ?), Trace of sand ejection was found.
9	Shikichi ,Toku-shima, 2km	Late Kofun era (the 4th to 5th century, ?), Ninna (Nara era/887), a sand ejection went up to a sedimented layer of Nara era through athat of Kofun era.
10	Kanyake, Kamiita,18km	Showa Nankai earthquake (1946)
11	Hiyoshidani, Awa, 37km	In the 3rd century B. C.(?), trace of liquefaction was found at a trace of dwelling house base.
13	Ohgaki, Miyoshi, 8km	Complex sand ejection of liquefaction. Mainly from the 6th (Aska era/599) to Keicho (Edo era/1605) and Jyoumon era/ 20,000 B. C.). <u>Kawarakemen area</u> : A trace of liquefaction measuring L38×W18 cm in the 5th century. <u>Ohtsubo area</u> : Kofun era (the 5th century) area was covered with elapsed sand of W 20 to 40cm(EW to NS) <u>Oh-hunato area</u>: Hushimi-Keicho (Edo era/1596, 1605 or 1594?): A liquefied pad field was found. The sand ejection of L200×W3cm penetrated through the pad field from South to North .

*: Distance from the mouse of River Yoshino

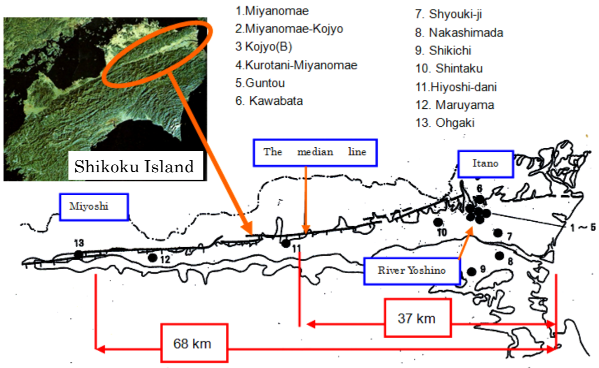


Fig. 3 Location map of investigated liquefaction trace in Tokushima (1999)

3 RE-CONSIDERATION OF LIQUEFACTION MECHANISM

From the investigation reports at relict sites showed phenomena of the repeatability and selectivity of liquefaction. A committee of ASCE defined the term, that liquefaction is "a process or behavior of solid soil to become a liquid state due to decrease of effective stress with increase of pore water pressure, Δu_e, in a soil element", however, an important issue is the reason why pore water pressure in a soil element accumulates during a cyclic shear, namely mechanisms of liquefaction is a question. In order to address this, a series of a standard CD test and cyclic CD/CU tests, were performed.

Fig. 4 shows a shear stress, τ and ΔH (dilatancy) to D (horizontal displacement) relationships from a standard direct shear test on a dry sand sample of e_0=0.85. The peak strength of 34.6kN/m^2 is obtained at D =2.4mm, and the greatest shrinkage of the sample was observed at D=0.5mm. Based on the results, a cyclic test was designed in which horizontal displacements of ±0.5mm were sheared on a sample.

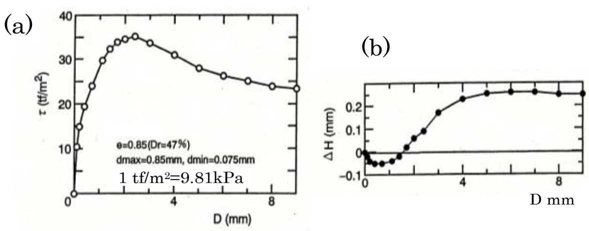
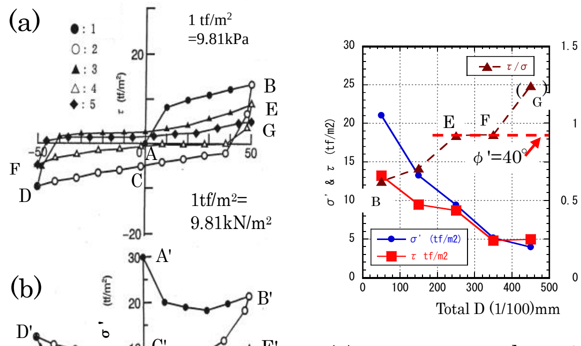


Fig. 4. Direct shear test under CD condition (Minamimori-machi sand, dry, σ_0=29.4kPa, e_0=0.85, Dr=47%)

Fig.5 shows results from a cyclic loading test under CU condition on the same sand. Fig.5(a) is a diagram for relationships of τ to D, and Fig.5(b) is that of σ' to D. Fig.(c) is a diagram of σ' or τ to total displacement (Total D). In the diagram, relationships of τ/σ' to total D are also shown by a dotted line. It is found that the ratio, τ/σ' did not increased lineally to increase of σ', with a peak at a line of φ'= 40°. The cyclic shearing caused to decrease of σ', or increase of Δu_e (as Δu_e=σ-σ'), whose phenomena is generally referred as accumulation of excess pore water pressure.



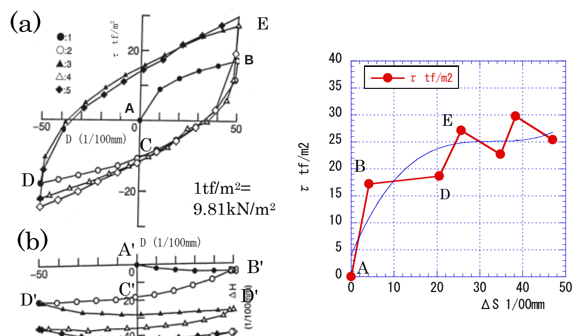
(c) σ', τ and τ/σ' to *Total D* diagram

Fig. 5 Cyclic test under CU condition (σ_0=29.4kPa, e_0=0.85, dry)

4 PROPERTY OF HOMOGENIZATION DUE TO CYCLIC SHEARING

Fig.6(a) and 6 (b) show results of a cyclic CD test on the same sand. The first shear to the front direction of +0.5mm that caused shrinkage due to dilatancy, ΔS, of -0.05mm, which coincides with the data shown in Fig.4(b). Then, the following shearing to back direction caused -0.21mm shrinkage (ΔH/H=-1.05%) at -0.5mm of D. Then, the second shearing to forward direction showed shrinkage of -0.28mm (ΔH/H=-1.4%). The successive cyclic shear was carried out with displacement of ±0.5 mm, in which continuous increase of ΔS was observed. It was found that the sample's shrinkage of a cyclic test was different from that of standard CD test after D of +0.5mm.

Fig.6 (c) shows a diagram of τ to ΔS from the cyclic test, in which a regression curve of τ to ΔS was obtained, however, the relationships did not became a linear curve, whose trend of the curve is differ from that of ordinary CD tests.



(c) τ～ΔS diagram

Fig. 6 Cyclic test under CD condition (σ_0=29.4 kPa, e_0=0.85,dry)

Therefore, it was considered that increase of ΔS (or density) does not mean "real increase of density" of a sample, but an phenomenon which relates with a mechanism of homogenization of the sample, which induces that the increase of apparent density due to change of soil fabric can't be expected to increase shear strength so much. So, it can be understandable that an area, once liquefied, will suffer liquefaction several times, and the essence of the mechanism is not accumulation of Δu_e, but a process of homogenization of a sample.

Fig.7 shows stress paths of σ' and τ from cyclic CU tests for the same sand with void ratios of e_0=0.95 and 0.75. The consolidation stress for the samples was 68.7kPa. From the result of a sample of e_0=0.75, the effective stress, σ', decreased gradually along with increase of cyclic loadings, and the effective stress paths drew a form resembling a letter of 8.

Regarding to a test of e_0=0.95, the effective stress, σ', decreased abruptly along with a cyclic loading, and σ' on the stress path approached to be almost zero, showing a condition of liquefaction of a sample. Here, it should be noted that behavior of the stress path of an e_0=0.95 sample shows the same trend as that of an e_0=0.75 sample, which suggests that a possibility to be liquefy depends on boundary conditions of a layer regardless being a loose or dense, a sand or gravel, a saturated or unsaturated, or a shallow or a deep. It is also interesting that their stress paths cannot exist outside of their strength curve of φ'= 38～40°. Regarding to induced pore water pressure, Δu_e, it is considered that magnitude of it depends on that of overburden pressure, theoretically. This induced that liquefaction happens by chance only when "a blowout root" is developed in the overburden layers. This is a reason that a sand eruption sometimes delays to occur after an earthquake. It is also understandable that a blowout root forms a chained lines of sand ejection in the ground.

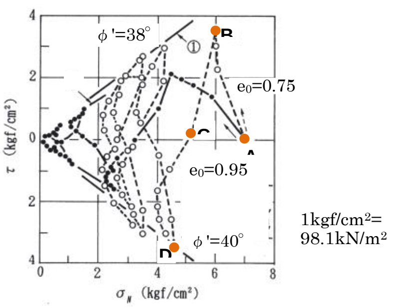


Fig. 7. Stress paths of cyclic tests under CU condition (σ_0=68.7kPa, e_0=0.85, dry)

5 CONCLUSION

Liquefaction phenomena have been one of research targets for a long time. However, some of concepts of them were remained to be misunderstood.

From this research, first, it was shown that records of archology from relict sites were drastically effective to investigate properties of liquefaction phenomena.

Second, liquefaction properties of repeatability, selectivity, accumulation of pore water pressure, Δu_e, which terms were defined in this paper, were discussed.

Third, in order to understand those phenomena, two series of cyclic CU or CD tests on sand were performed, in which cyclic shearing caused homogenization of a sample. And, it is considered to be a reason for phenomena of repeatability of liquefaction. Phenomena of accumulation of Δu_e and a time delay eruption of liquefaction were also discussed.

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