Paper No. 362. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

DEVELOPMENT OF A LIQUEFACTION SENSOR

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ABSTRACT

A sensor to detect liquefied sites immediately after an earthquake was developed, enabling quick action to be implemented and prevent further pipeline damage due to liquefaction. The "liquefaction sensor" measures the rise of the water level inside a hollow pipe inserted in the ground. This paper outlines the development of the sensor, including the results of laboratory shaking table tests, boiling tests and field vibration tests which showed that the water elevation inside the pipe is proportionately related to the excess pore water pressure. This paper also reports the response of sensors to actual earthquakes, which may verify this adaptability. The magnitude of these earthquakes was small and pore water pressure was low, but the water level rise was almost equal to the recorded maximum pore water pressures in the adjacent ground.

KEYWORDS

Liquefaction, Liquefaction sensor, Pore water pressure, Liquefaction detection method, Water level rise, Adaptability test.

INTRODUCTION

Severe earthquakes in the past have shown that liquefaction of the underground soil mass is the predominant cause of damage to buried gas pipelines. This was clearly exemplified by the 1964 Niigata Earthquake and the 1983 Nihonkai-Chubu Earthquake, where underground gas pipelines suffered extensive damage as a result of the liquefaction of soil deposits (Japan Gas Association, 1965; 1984). Therefore, if the occurrence and extent of liquefaction can be detected at the site of underground gas pipelines, then efficient measures can be immediately implemented to prevent further damage to such facilities.

The surest method for directly detecting the occurrence of liquefaction within a short period after an earthquake is to measure the changes in the pore water pressure. However, conventional pore water pressure meters are unreliable for long term measurements. Therefore, a more durable sensor is required for continuous monitoring of pore water pressure build-up. With this in mind, a "liquefaction sensor" has been developed which detects the occurrence and extent of liquefaction based on the rise of the water level inside a hollow pipe inserted in the ground.

This paper outlines the development of liquefaction sensors. The results of various laboratory tests (shaking table tests, boiling tests) and field tests (vibration tests) conducted to examine the effectiveness of the model sensors are presented. The response of sensors installed at various sites within the Tokyo Metropolitan Area during recent minor earthquakes is also discussed.

EXPERIMENTS ON WATER LEVEL RISES INSIDE A HOLLOW PIPE

The liquefaction sensor is a device that detects the occurrence and extent of soil liquefaction by measuring the water level in a pipe buried underground. Although its working principles are quite simple, several experiments were conducted to confirm the relationship between the water level in a hollow pipe buried underground and the excess pore water pressure generated in the adjacent ground. For this purpose, several shaking table and boiling tests involving a soil container and model pipes were carried out under several test conditions.

In the shaking table tests (Yasuda et al., 1990), two pipes with strainers, one with a diameter of 11.8mm and the other 46.5mm, were placed in a soil model (D_r = 10~24%, F_c = 16.4%) measuring 90cm long, 50cm deep and 60cm wide. The model ground, shown in Fig. 1 (a), was then shaken so as to make the pore water pressure in the ground rise to a pre-determined level. Then, the water elevation in the pipes as well as the excess pore water pressure were measured. Fig. 1 (b) shows the results of the tests in terms of the relationship between the maximum excess pore water pressure ratio, $\Delta u/\sigma'$, in the adjacent ground (based on Transducer No. 5) and the maximum water levels, ΔH, in the pipes. It can be seen from the figure that the water elevation rises to a higher level as the pore water pressure is increased, and that the two variables have nearly proportional relationship.

In these tests, it was noted that, due to the small ground area of the model, the excess pore water pressure dissipated immediately after shaking and the pore water pressure could not be maintained for a long time. In the ground itself, however, the excess pore water pressure is maintained for a long time due to the presence of unliquefiable layers above the liquefiable deposit. In order to simulate this condition, boiling tests were also conducted to test the adaptability of the sensors (Yoshihara, et al., 1992).
The boiling tests were performed in a small tank into which the model ground (D_r = 43%, F_c = 3%) was placed.

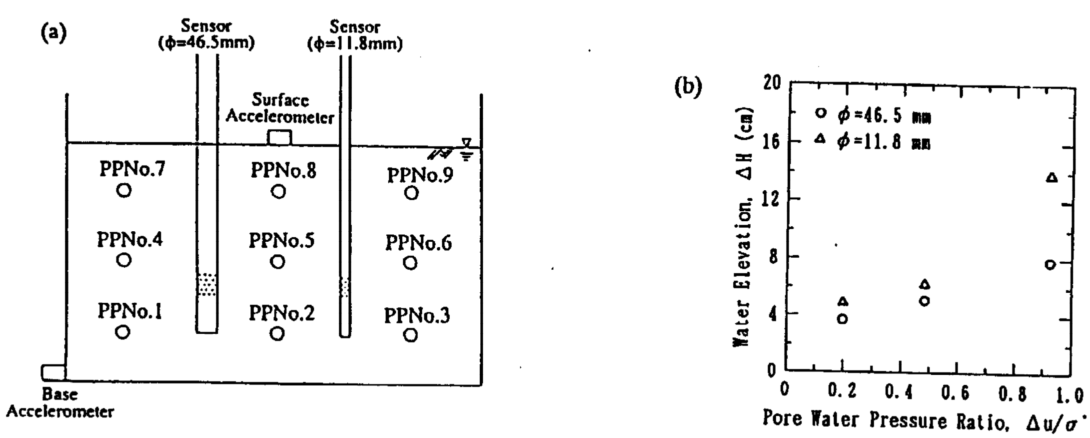

Fig. 1. (a) Experimental set-up of shaking table test:
(b) Relation between $\Delta u/\sigma'$ and ΔH

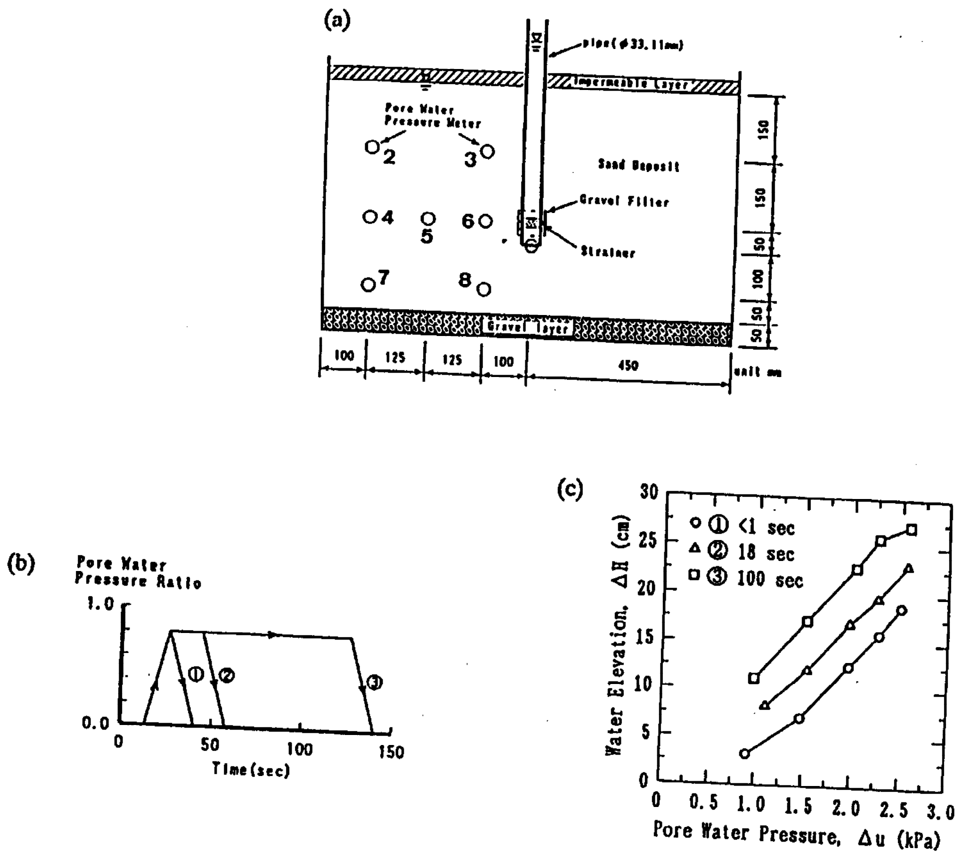

Fig. 2: (a) Soil tank used in boiling experiment;
(b) Water pressure supply pattern
(c) Results for various supply time

The experimental set-up is shown in Fig. 2 (a). Again, a hollow pipe was embedded in the model ground to act as "sensor". Water was then introduced into the model ground such that the pattern of pore water pressure build-up was constant, as illustrated in Fig. 2 (b). The water elevations inside the pipes were again monitored. In these tests, the effects of various parameters, such as fines content, relative density, length and depth of strainer, pipe diameter, supply duration time and ground surface conditions, were investigated.

Fig. 2 (c) illustrates the results where only the water supply duration time was varied and all the other parameters were constant. The pore water pressures shown were those monitored by Transducer No. 4. It can be seen that as the pore pressure increases, there is a proportional increase in water level height for each specific supply duration time.

The results of the shaking table and boiling tests confirmed that the elevation of the water level in the pipe is nearly proportional to the excess pore water pressure in the adjacent ground. The results of these experiments gave rise to the development of "liquefaction sensors" (Shimizu et al., 1992).

OUTLINE OF LIQUEFACTION SENSOR

As mentioned earlier, the liquefaction sensor is a device that can quickly detect the occurrence and extent of soil liquefaction during earthquakes.

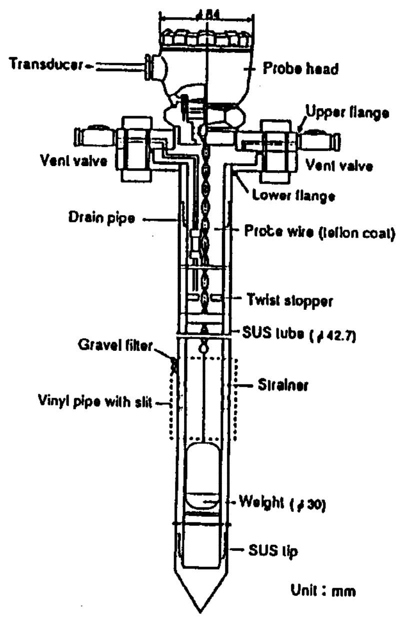

Fig. 3: Schematic diagram of liquefaction sensor

Fig. 3 shows the schematic drawings of the sensors. The sensor basically consists of a hollow pipe buried underground with a strainer that takes in the underground water and raises the water level in the pipe, and a water level detection sensor that measures the amount of water elevation within the pipe. A capacitance type level gauge currently used for widely water tank level gauges was modified to use as a detection sensor.

The inside diameter of the stainless steel pipe is 32.9mm. The strainer section, which is 100mm long and has openings of 2mm in diameter, is positioned in the sandy layer which is susceptible to liquefaction. A filter utilizing the gravel screening method is provided in the vicinity of the strainer to prevent the entry of soil particles.

As no sophisticated instruments are used underground, the life of the sensor is enhanced. Moreover, most of the detecting devices can be accessed above the ground and, therefore, maintenance work is easier.

At present, Tokyo Gas Co., Ltd. has installed liquefaction sensors at 20 sites across the Tokyo Metropolitan Area. The data recovered by the sensors is transmitted quickly to the head office through a wireless network. If certain areas are evaluated on this data to have some damage to gas pipelines, the gas supply is closed off to prevent further damage to other structures.

IN-SITU VIBRATION TEST FOR SENSOR ADAPTABILITY

The liquefaction sensors outlined above have been subjected to in-situ test in order to verify their adaptability. For this purpose, prototype sensors have been installed in-situ and subjected to vibration tests.

The site for full scale vibration tests was a reclaimed land area in Tokyo Bay. Based on boring date at the site, a fine sand layer (SPT N-value < 10), which seems to be liquefiable when subjected to vibration, exists at depths ranging from GL-1.0m and GL-3.25m. Two liquefaction sensors with different strainer lengths, seven

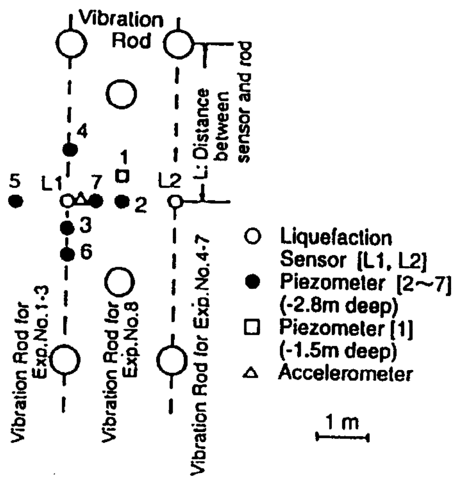

Fig. 4: Set-up for full-scale vibration test

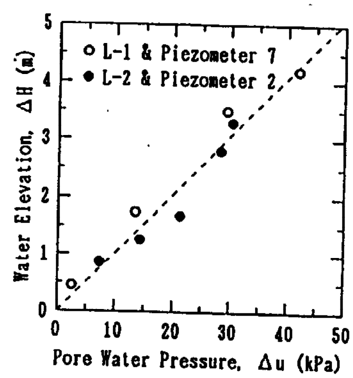

Fig. 5: Results of vibration test

pore water pressure transducers and one accelerometer were installed at the site. The arrangement of these measuring devices is shown in Fig. 4. The centers of the sensor strainers were positioned at a depth of GL-2.8m. Six of the pore pressure transducers were buried at the same depth as the strainers, while one transducer was buried at a depth of GL-1.5m.

Ground vibration was generated by the insertion of a pair of vibration rods into the ground by vibro-hammers. The rods were located symmetrically with respect to the sensors, as shown in Fig. 4. The tests were carried out by varying the distance between the sensors and the vibration rods. The excess pore water pressures as well as the water elevation in the pipes were monitored.

Fig. 5 shows the relationship between the maximum excess pore water pressure, Δu, measured by the piezometers and the maximum water elevation in the sensors, ΔH. It can be seen that there is a linear relationship between the two parameters, confirming the effectiveness of the sensor as a device to measure liquefaction.

RESPONSE OF SENSORS TO ACTUAL EARTHQUAKES

Over the past several of years, the Tokyo Metropolitan Area has been shaken by several minor earthquakes. A notable example is the one which occurred on May 21, 1993 (M5.4; maximum intensity of IV on the JMA scale). Although the earthquakes were of small magnitude and the pore pressure was generally low, it nevertheless triggered an increase in water level inside some of the liquefaction sensors installed in the area. The recorded values at Sasamegawa site during the May 21, 1993 earthquake are shown in Fig. 6. The peak ground acceleration registered is 113.7 gals, and the water level in the sensor rose to about 6cm, which was almost equal to the maximum recorded pore water pressure in the adjacent ground.

Based on this observations, the water levels in the sensors can be expected to increase when sufficient excess

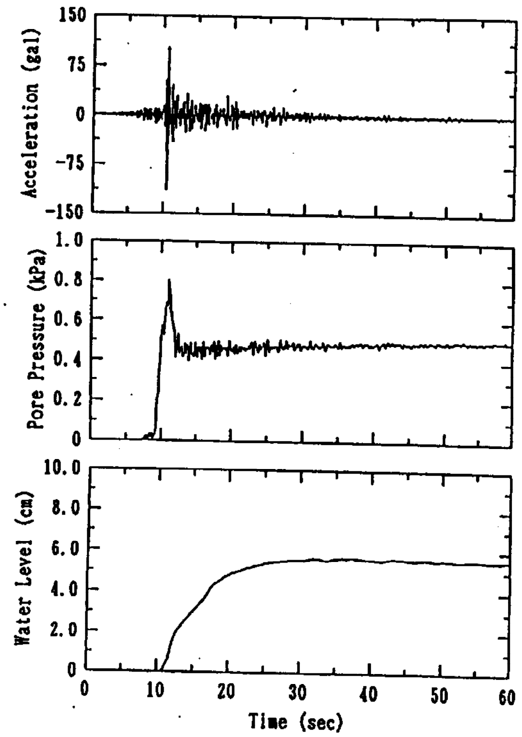

Fig. 6: Recorded surface acceleration, pore water pressure and water level at Sasamegawa site during the May 21, 1993 earthquake

pore water pressure is generated in the ground. It is believed that during large earthquakes when pore pressure build-up is normally high, the rise in the water level inside the sensor would be indicative of the degree of soil liquefaction.

CONCLUDING REMARKS

For the purpose of mitigating the damage to underground gas pipelines caused by the soil liquefaction, "liquefaction sensors" which measure the rise in water elevation inside a hollow pipe inserted underground have been developed. The adaptability of the sensors has been extensively validated through laboratory shaking table tests, boiling tests, and in-situ vibration tests.

Tokyo Gas Co., Ltd. has installed liquefaction sensors at 20 sites and several small-scale earthquakes have triggered rises in the level of water inside these sensors. The magnitude of these earthquakes was small and pore water pressure was low, but the water level rise was almost equal to the recorded maximum pore water pressures in the adjacent ground. It is believed that the sensor will provide more explicit data given a higher level of earthquake excitation and pore pressure build-up.
The operating conditions of the liquefaction sensors are being further refined to improve their performance, and, with these additional efforts, it is hoped that the liquefaction sensor will prove effective as a method to mitigate the damaging effects of soil liquefaction during earthquakes.

ACKNOWLEDGMENTS

The authors would like to thank Dr. S. Yasuda of Tokyo Denki University, Mr. K. Tsukamoto of Tokyo Gas Co., Ltd, Mr. I. Morimoto and Mr. T. Miyazaki of Kiso-jiban Consultants, who also contributed to the development of the liquefaction sensor.

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