EXPERIMENTS ON DAMAGE MITIGATION OF BURIED PIPELINES DUE TO LIQUEFACTION

Masaru MITAURA*
Masakatsu MIYAJIMA**
Presenting Author: Masaru KITAURA

SUMMARY

In past severe earthquakes, a great amount of heavy damage has been caused not only by seismic wave propagation but also by ground failure such as liquefaction, landslides and faults. The liquefaction-induced dynamic behavior and failure criteria of buried pipelines have, however, not been made clear. Therefore, it is important to understand the dynamic responses of a buried pipeline during an earthquake and to consider how to prevent this damage. This paper deals with the vibrating tests employing a rubber pipe model in the liquefaction process. The pipe strain characteristics during liquefaction are investigated and a procedure for mitigating the damage due to liquefaction is given.

INTRODUCTION

Embedded pipeline systems have been damaged extensively by several recent severe earthquakes, for example, the 1971 San Fernando earthquake in the U.S., the 1978 Miyagiken-Oki earthquake in Japan, etc. On the other hand, the liquefaction of sandy soil caused large damage to buildings and embedded pipeline systems in the 1964 Niigata earthquake and the 1983 Middle Japan Sea earthquake in Japan. Many studies of liquefaction have been performed very actively. From the results of these studies, the mechanism of the liquefaction phenomenon has become almost clear. However, despite the remarkable achievements in the study of liquefaction, several major problems remain to be solved. One of them is the interaction between the liquefied soil and underground structures. So far, not much work has been done on the liquefaction-induced dynamic behavior of a pipeline and the effective countermeasure for mitigating the damage due to liquefaction [1,2]. This paper deals with the vibrating tests using a rubber pipe model in the liquefaction process. The pipe strain characteristics during liquefaction are investigated and a procedure for mitigating the damage due to liquefaction is given.

STRAIN CHARACTERISTICS OF THE PIPE

Fig. 1 shows a general view of the experimental apparatus. The size of the model sand stratum was 500 mm in width, 1500 mm in length and about 250 mm in height. The buried pipe model was a rubber stick with 20 mm diameter and 1000 mm in length. Its elastic modulus was 810 kg/cm^3 (79.4MPa) and its

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* Associate Professor, Department of Construction and Environmental Engineering, Kanazawa University, Japan, Presently Visiting Research Scientist, Department of Civil Engineering and Engineering Mechanics, Columbia University, U.S.A..

** Research Associate, Department of Construction and Environmental Engineering, Kanazawa University, Japan.

weight per unit volume was 1.14 g/cm^3 (11.2 kN/m^3). Strain gauges were pasted on it and waterproofed. A pore pressure transducer was embedded at the same depth as that of the model pipe to measure the excess pore water pressure during liquefaction. The model sand stratum was vibrated by a harmonic wave with a frequency of 5 Hz for 30 seconds. The shaking direction was parallel to the axis of the pipe.

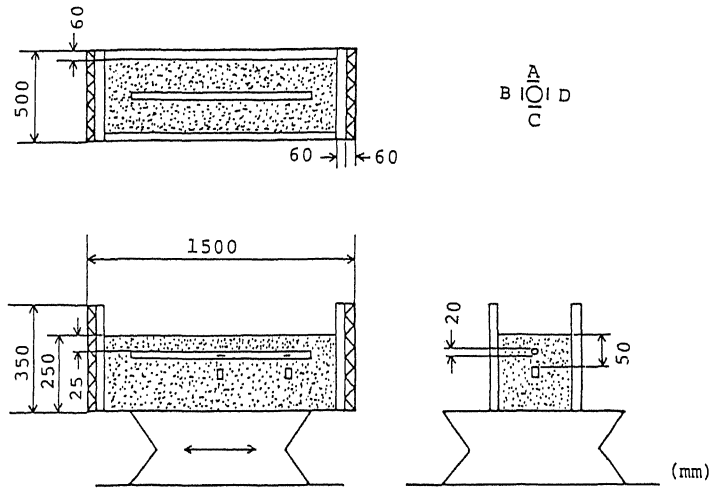

Fig. 1 General view of experimental apparatus.

Vibrating tests were carried out employing the model pipe, whose two ends were free and buried in loose, saturated sand strata. This model simulated the pipelines embedded in a free field. Fig. 2 displays the strains and excess pore water pressure. A, C, B and D indicate the upper and lower strain gauges and those of the two sides at the center of the pipe, respectively. The pipe was buried at a depth

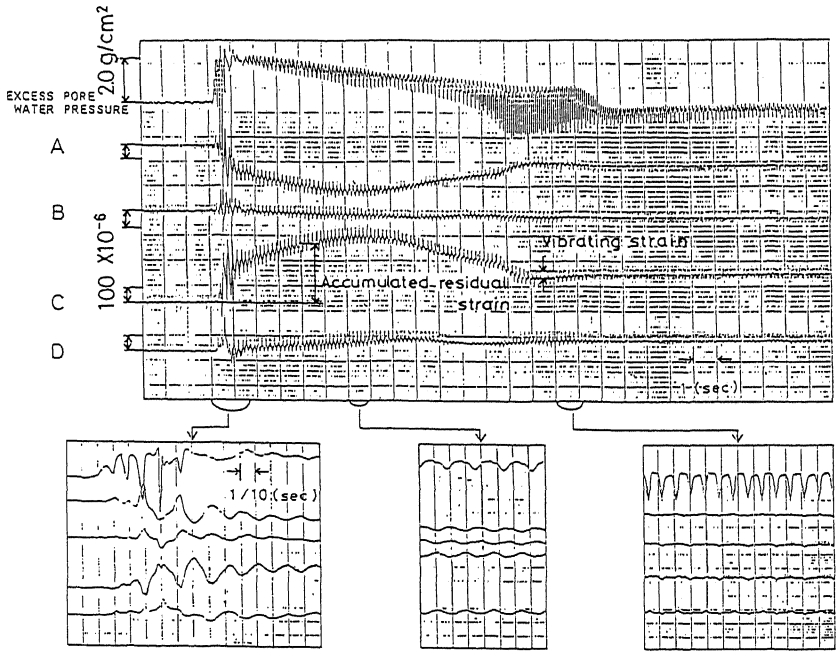

Fig. 2 Records of excess pore water pressure and strains of the pipe.

of 25 mm. As the excess pore water pressure rose and fell, large pipe strains were caused. The pipe strains consist of accumulated residual and vibrating strains. The accumulated residual strain is expressed by the transfer distance of the neutral axis in the strain records and the vibrating strain is expressed by the vibrating strain amplitude (see Fig. 2). The former strain is due to pipe bending and the latter is that due to pipe vibrating. As is shown in Fig. 2, the upper and lower strain gauges indicate the tensile and compressive strains, respectively, during liquefaction. This suggests that the model pipe bends at the center due to the buoyancy generated by the soil liquefaction in the model ground. As far as the maximum value is concerned, the accumulated residual and vibrating strain were abuot 240 x 10^{-6} and 120 x 10^{-6}, respectively. The maximum accumulated residual strain was larger than the maximum vibrating strain. As a result, the strains caused by pipe bending dominate those due to pipe vibrating in this case.

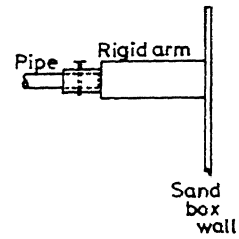

Fig. 3 Fixed end of the pipe.

Experiments were also performed using the model pipe with one end fixed which was the model of a pipeline connected to a building. The past severe earthquakes have caused much damage at that end. The end of the model pipe was fixed by a rigid arm set on the sand box (see Fig. 3). Fifteen strain gauges were pasted on the model pipe and waterproofed. They were numbered 1-19 (see Fig. 4). The pipe was buried at a depth of 40 mm in these experiments. Other experimental conditions were the same as those in former experiments. Fig. 5 illustrates the pipe strain records at gauge numbers 1 (nearest to the fixed end), 4, 7 and 10, and the excess pore water pressure record. The vibrating

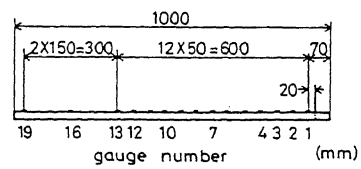

Fig. 4 Model pipe.

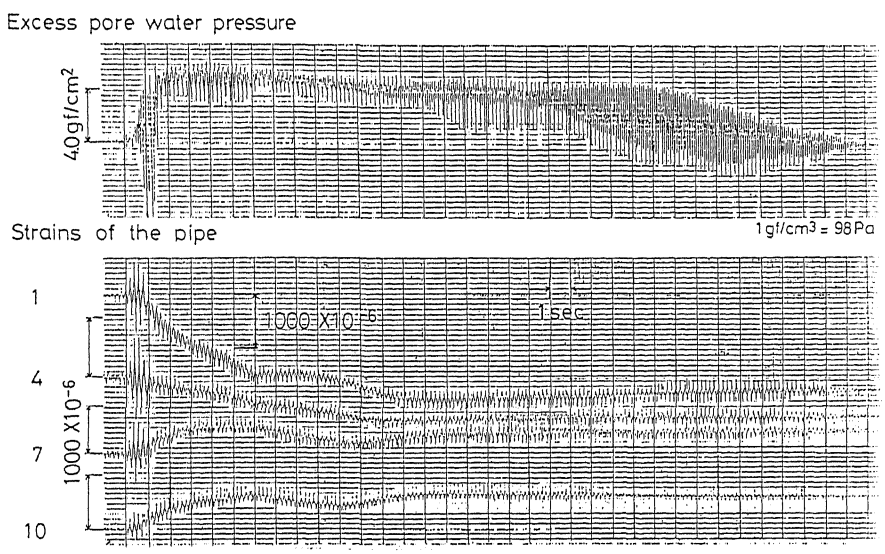

Fig. 5 Records of excess pore water pressure and strains of the pipe.

strains increased as the model ground was incompletely liquefied and also as the liquefaction dissipated. This agrees with former experimental results. When the model ground was completely liquefied, the strains were greater than those in the former experimental results because the input wave was transmitted to the pipe from the fixed end in this case. Figs. 6 and 7 display the strain distribution. Fig. 6 shows the maximum accumulated residual strains. The strain gauges near the fixed end (Nos. 1-5) showed compression and the others tension. Gauge number 1 (nearest to the fixed end) indicated about 2000 x 10^{-6} which was the maximum accumulated residual strain. Fig. 7 shows the mean vibrating strains. Since the input wave did not transmit from the model ground but rather transmitted from the fixed end during liquefaction, the vibrating strains near the fixed end were large. The maximum vibrating strain in the time records was about 500 x 10^{-6} at gauge number 1.

As shown above, it is now apparent that the accumulated residual and vibrating strains are large near the fixed end and that the maximum accumulated residual strains are much larger than the maximum vibrating strain. This suggests that the probability of failure due to pipe bending is large at this point.

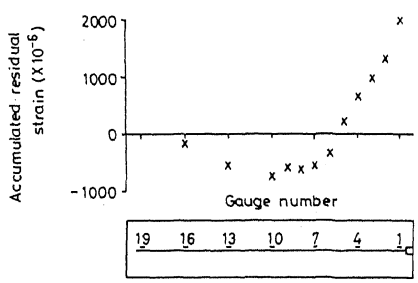

Fig. 6 Distribution of maximum accumulated residual strains.

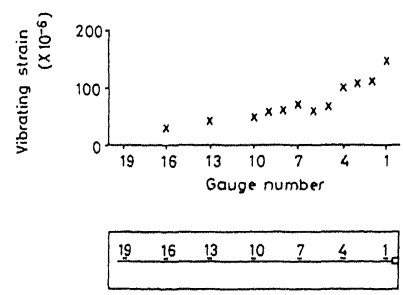

Fig. 7 Distribution of mean vibrating strains.

EFFECTS OF GROUND COMPACTION ON PIPE STRAINS

The model ground near the fixed end of the pipe was improved by compaction to reduce the large accumulated residual strains. The placement of strain gauge nember 10 coincided with the boundary ground between the densified and loose sand strata. Fig. 8 illustrates the strain records at strain gauges 1, 4, 7 and 10, and the excess pore water pressure in the densified and the loose sand strata. Gauge numbers 7 and 10 indicated large vibrating strains during several seconds. And the excess pore water pressure in the densified sand stratum increased slightly. These results suggest that the model ground around strain gauge numbers 7-10 became soft. This was interpreted in terms of the groundwater flow from the loose sand stratum to the densified one. Fig. 9 and 10 show the strain distribution. Fig. 9 displays the maximum accumulated residual strains. The pipe deformation after liquefaction is shown in Fig. 11. Since the strain gauges were pasted on the upper part of the pipe, the content of Fig. 9 was found to be consistent with that of Fig. 11. The model pipe bends slightly at the boundary ground softening around strain gauge numbers 7-10. Ground softening has the effect of mitigating the accumulated residual strains concentrated at the boundary

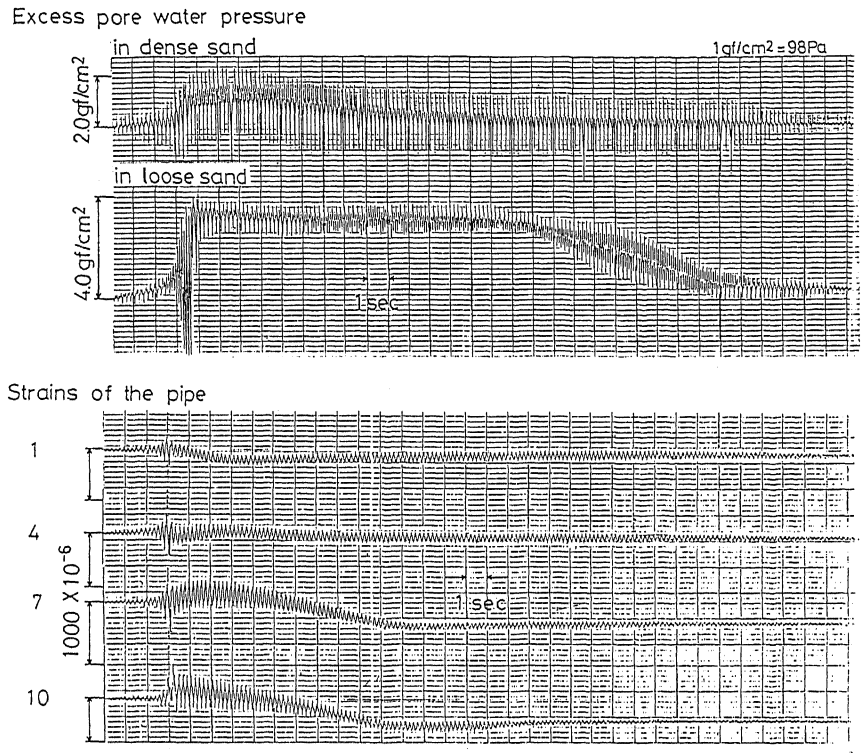

Fig. 8 Records of excess pore water pressure and strains of the pipe.

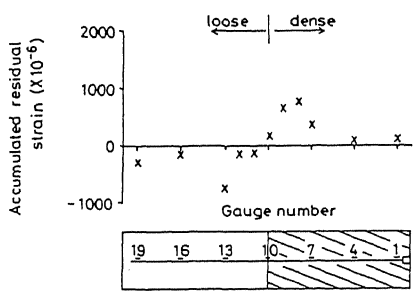

Fig. 9 Distribution of maximum accumulated residual strains.

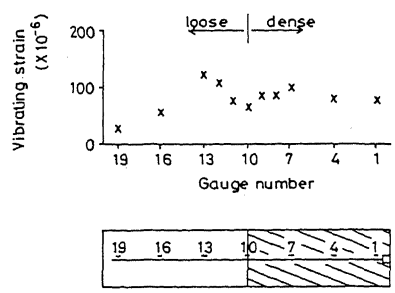

Fig. 10 Distribution of mean vibrating strains.

ground. The maximum strain in Fig. 9 was about 750 x 10^{-6} at strain gauge numbers 8, 9 and 13. It was much smaller than that in Fig. 6: 2000 x 10^{-6}. Fig. 10 shows the mean vibrating strains. The vibrating strains near the boundary ground were large. The maximum vibrating strain in the time records was about 500 x 10^{-6} at gauge number 7. This was similar to former experimental results.

As a consequence of these experiments, the sand compaction of the model

ground reduced the accumulated residual strains, even though it caused large vibrating strains at the boundary ground between the loose and densified sand strata.

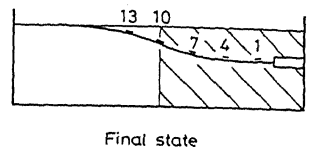

Fig. 11 pipe deformation after liquefaction.

EFFECTS ON PIPE STRAIN OF INCREASING WEIGHT PER UNIT VOLUME OF PIPE

In general, the weight per unit volume of a water supply pipe filled with water is lighter than that of liquefied soil. Fig. 12 shows the ratio of buoyancy acting on a ductile iron pipe during liquefaction to the weight of a pipe filled with water. This figure proves that the ratio of the buoyancy to the weight is 130% or so without reference to the nominal diameter. This means that the probability of a pipe floating during liquefaction is great in water supply systems.

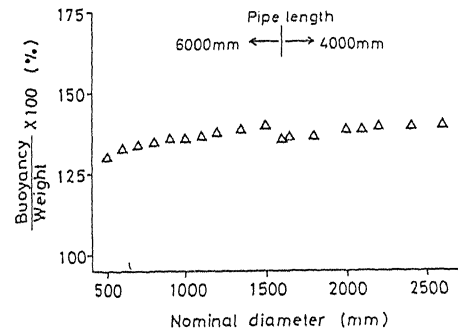

Fig. 12 Ratio of buoyancy to weight per unit volume of water supply pipe filled with water.

In order to prevent floating of the pipe during liquefaction, a model pipe with increased weight was buried in unimproved ground. Its weight per unit volume was changed from 1.14 g/cm^3 (11.2 kN/m^3) to 1.81 g/cm^3 (17.7 kN/m^3). Fig. 13 displays the pipe strain records at gauge number 1, 2, 3 and 4 (near the fixed end), and the excess pore water pressure. This figure shows that the accumulated residual strains are not so large in spite of the model ground liquefying. The deformation of the pipe was 2 or 3 mm at the free end after liquefaction. Flexibility of the pipe was reduced in these experiments. The effects of reducing the flexibility were considered, however it was concluded that increasing the weight of the pipe reduced pipe deformation.

As shown above, these experimental results indicated that the accumulated residual strains were markedly reduced. This was explained in terms of no floating of the heavier pipe due to buoyancy during liquefaction. Therefore, it is concluded that increasing the weight per unit volume of the pipe is an effective countermeasure to prevent pipe floating due to liquefaction.

CONCLUSIONS

The countermeasure for mitigating the damage due to liquefaction can be classified into the following two types. One is a countermeasure to the surrounding soil and the other is to structures. As far as the former is concerned, this paper deals with ground compaction near the fixed end. On the other hand, increasing the model weight is used as the latter measure. The

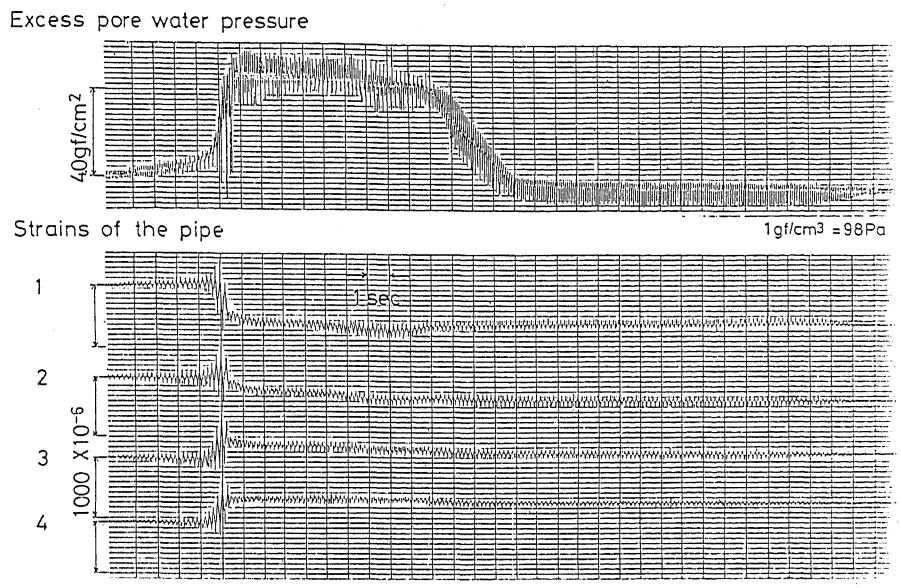

Fig. 13 Records of excess pore water pressure and strains of the pipe.

experimental results lead to the following conclusions. The pipe strains consist of the vibrating strain due to pipe vibration and the accumulated residual strain due to pipe bending. They are concentrated near the fixed end and the latter is much larger than the former.

Compacting the surrounding ground is an effective measure for mitigating the accumulated residual strains concentrated at the fixed end. On the other hand, the densified ground softening at the boundary ground causes large vibrating strains lasting several seconds. Therefore, care should be taken of the dynamic, flexural behavior of a pipe located between loose and densified areas. Furthermore, it is interesting to note that increasing the weight per unit volume of the pipe is also an effective countermeasure to prevent pipe floating due to liquefaction.

REFERENCES

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