# Quantitative Analyses on Damage to Buried Pipelines due to 1983 Middle Japan Sea Earthquake

Masaru KITAURA* and Masakatsu MIYAJIMA*

**Abstract**

*The 1983 Middle Japan Sea Earthquake (M = 7.7) which occurred off the west coast Akita Prefecture caused extensive damage to lifeline systems. The authors already reported the results of field investigations. The present paper discusses the damage to the buried pipelines due to liquefaction. The purposes of the present study are to analyze the damage of pipelines quantitatively employing a statistical method and to make clear the failure mode of the buried pipeline. It became evident from the present study that the damage to pipelines was strongly influenced by the state of ground, especially soil liquefaction.*

## 1. Introduction

The damage due to the 1983 Middle Japan Sea Earthquake is classified into two items:
(1) Many losses in men and damage to the harbor facilities and ships which were caused by Tsunami.
(2) Damage to buried pipelines, fill-up ground, buildings, railroads and roads which were caused by soil liquefaction

The authors already reported the results of field investigations in Ref. 1) and the outline of damage to lifelines and their restoration in Ref. 2), respectively. The present paper disusses the damage to the buried pipelines due to liquefaction based on the detailed data which the authors obtained after finishing the report.

The purposes of the present study are to analyze the damage of pipelines quantitatively using a statistical method and to make clear the failure mode of the buried pipelines on the strength of the field investigation data mainly in Noshiro. This paper firstly describes the actual condition of the earthquake damage to pipelines in relation to the state of the ground, the material and diameter of pipes forming a pipeline. After that, it shows the results of the multivariate analysis, which is often called "the Quantification Theory 1", concerning some influential items. Secondly the failure mode of the buried pipelines is discussed based on the investigated results.

## 2. Relationship between State of Ground and Damage to Pipelines

### 2. 1 Number of Damage

The number of damage to the water supply and city gas pipelines is shown in Tables 1, 2 and Fig. 1. Table 1 indicates the damage ratio of the water supply pipelines[3]. The damage ratio is

*Department of Civil Engineering

Table 1 Number of damage of water supply pipelines (after Noshiro City Gas and Waterworks Bureau, 1983[3]).

| Kind of pipes | Length of pipeline(km) (A) | Number of damage (B) | (B)/(A) |
|---|---|---|---|
| ACP | 69.475 | 223 | 3.210 |
| CIP | 6.899 | 23 | 3.334 |
| VP | 40.726 | 210 | 5.156 |
| SP | 1.308 | 0 | 0 |
| DCIP | 23.167 | 5 | 0.216 |
| TOTAL | 141.575 | 461 | 3.256 |

Table 2 Number of damage of city gas pipelines (after Noshiro City Gas and Waterworks Bureau, 1983[3]).

| Kind of pipes | Length of pipeline(km) (A) | Number of damage (B) | (B)/(A) |
|---|---|---|---|
| ACP | 0.0 | 0 | - |
| CIP | 27.638 | 231 | 8.358 |
| VP | 3.361 | 0 | 0.0 |
| SP | 25.040 | 113 | 4.513 |
| DCIP | 0.978 | 1 | 1.022 |
| TOTAL | 57.017 | 345 | 6.051 |

defined as the number of damage divided by the total length of a pipeline in the present paper. This table means that the total length of the asbestos cement pipe (ACP) is the longest and the damage ratio of the polyvinyl chloride pipe (VP) is the highest of all kind of pipes. Table 2 shows the damage ratio of the city gas pipelines. This table reveals that the city gas pipelines mainly consist of cast iron pipe (CIP) and steel pipe (SP), and the former damage ratio is higher than the latter. Fig. 1 describes the relationship linking the diameter and damage ratio. This figure suggests as follows: the polyvinyl chloride pipe of water supply systems whose damage ratio is high has relatively small diameter, less than 150mm. The cast iron pipe with 400mm and 450mm diameter has very high damage ratio in spite that the cast iron pipes of the water supply pipelines show low damage ratio as a whole.

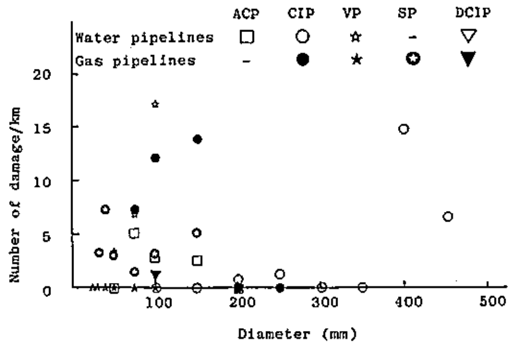



Fig. 1 Relationship between diameter of pipes and damage ratio.

In the point that the pipes with relatively small diameter of 50mm to 150mm were severely damaged, the greatest similarity can be seen in a comparison of the past earthquake damage to the pipelines. It is, however, interesting to note that the damage ratio of the pipes with large diameter, 400mm and 450mm is high. This will be discussed later.

## 2. 2 Influence of State of Ground

Figs. 2 and 3 are the distribution charts of SPT N-value up to 5m in depth and one of underground water table, respectively. These figures indicate the average value of each mesh which is one of 20 equal parts in length and breadth into which a one-to-twenty-five-thousand topographical map is divided. Fig. 3 reveals that the underground water table is high at the area of the lower reaches of Yoneshiro river and near to Asanai swamp. These areas coincide with the meshes which indicate low SPT N-value up to 5m in depth. Fig. 4 shows the relationship linking the SPT N-value up to 5m in depth and the damage ratio of the pipes based on the data of each mesh. The plots in this figure are somewhat scattered. The envelope curve of the plots,

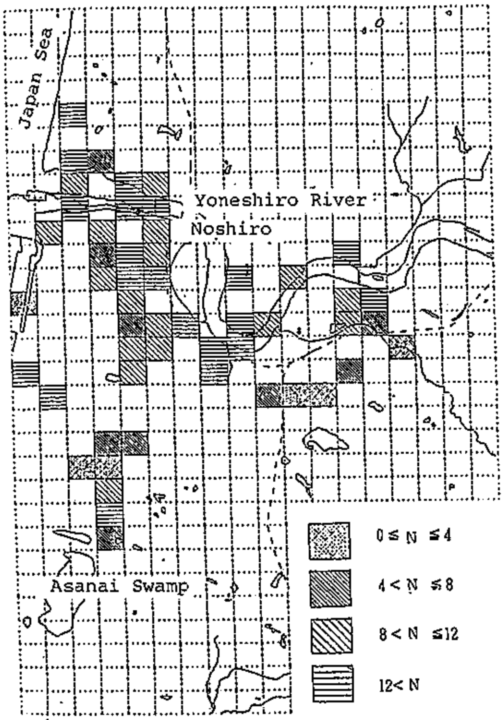



Fig. 2 Distribution of SPT N-value up to 5m in depth.

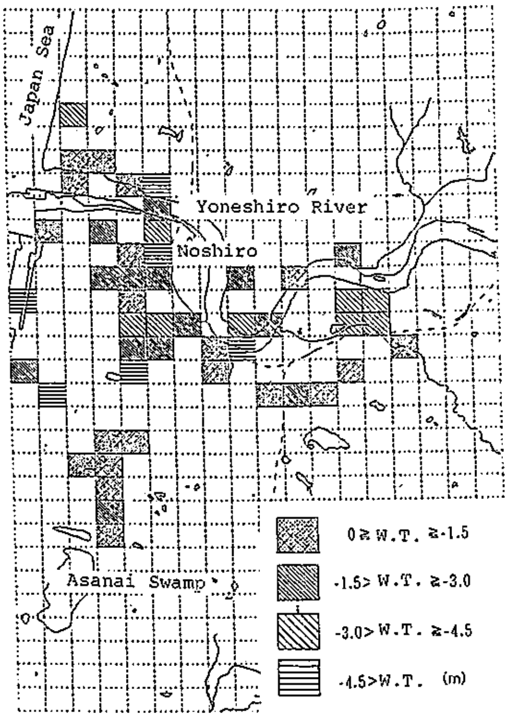



Fig. 3 Distribution of underground water table.

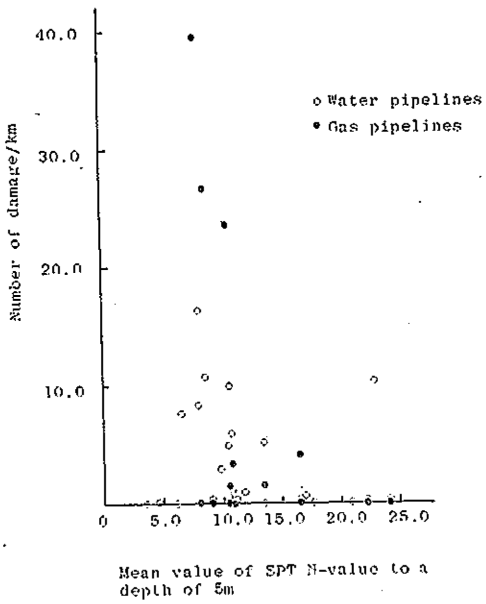



Fig. 4 Relationship between SPT N-value up to 5m in depth and damage ratio.

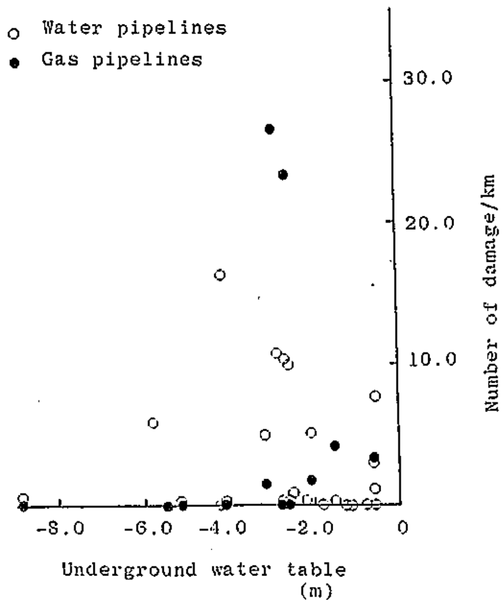



Fig. 5 Relationship between underground water table and damage ratio.

however, has a tendency that the damage ratio increases with a decrease in the SPT N-value up to 5m in depth. Fig. 5 indicates the relationship between the underground water table and damage ratio of the pipes. As in Fig. 5, the damage ratio of the pipes, whose underground water table is 1 to 3m, is high. This means that the damage ratio is high where the underground water table is near to the buried pipes.

Fig. 6, reported in Ref. 4), shows liquefied areas in Noshiro. Based on Fig. 6, we indicate the number of damage of the pipes in liquefied ground and that in non-liquefied ground in Fig. 7. This figure also shows the failure mode of the pipes in accordance with that in Fig. 8[3)]. It is evident from Fig. 7 that the damage to the pipes in the liquefied ground is heavier than that in the non-liquefied ground because the number of damage in both ground is no great difference in spite that the liquefied zone is much smaller than the non-liquefied zone. It is very interesting to note that all of the damage to the cast iron pipes were caused in the liquefied area and the damage was caused at joint of pipe.

These facts suggest the conclusion that the earthquake damage to the pipes depends on the state of ground, especially soil liquefaction. The influence of the soil liquefaction is quantitatively examined later.

There are some other factors besides the state of the ground which influence on the earthquake damage. The buried depth of pipelines is cited for instance, but the exact records are not kept except the data of the special cases. It is only noted that the general pipelines are buried at about 1.5m in depth. The buried direction of pipes may also influence on the damage, but the data to quantitatively investigate these effects are not obtained. These factors are not taken into consideration in the following analysis because of these reasons.

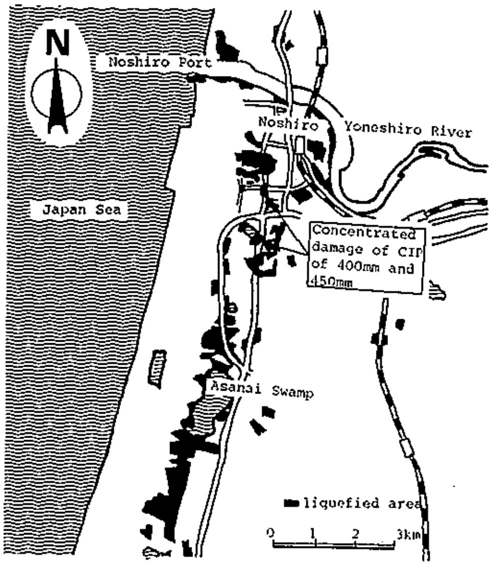



Fig. 6 Liquefied areas in Noshiro (after Tono, Yasuda and Shamoto, 1983[4)]).

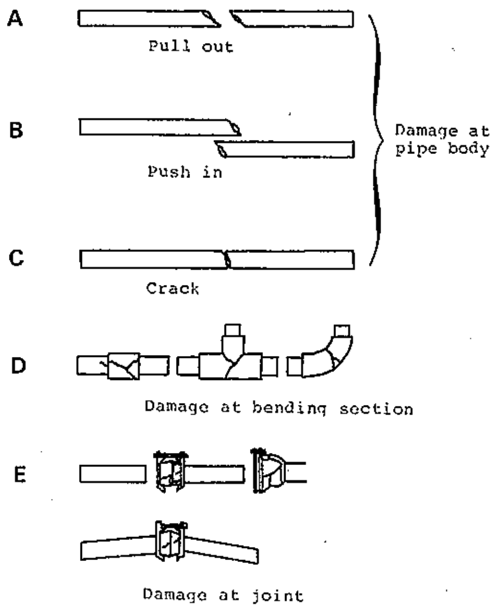



Fig. 8 Failure mode of pipe (after Noshiro City Gas and Waterworks Bureau, 1983[3)]).

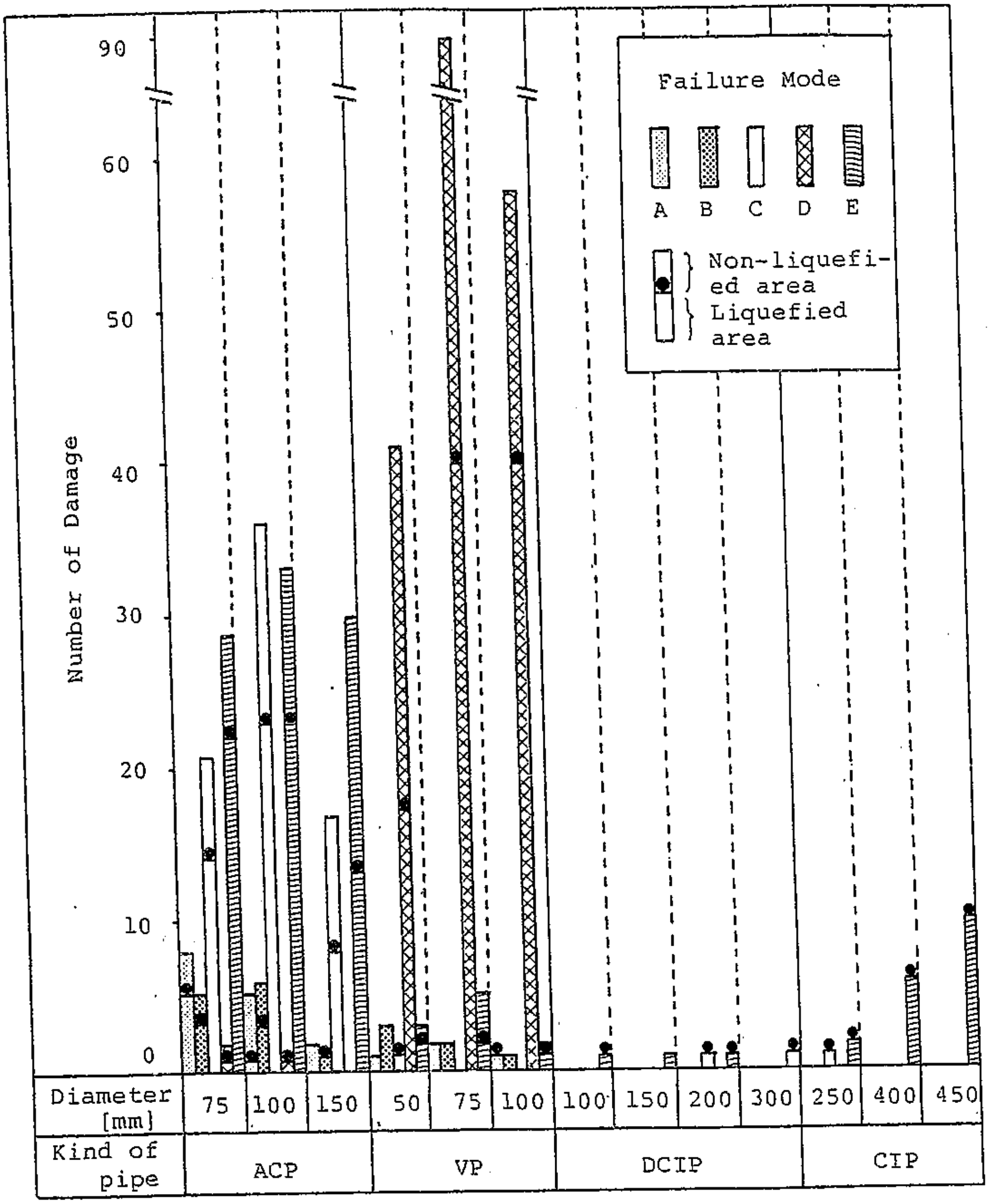



Fig. 7 Relationships between number of damage and failure mode.

## 3. Multivariate Analyses

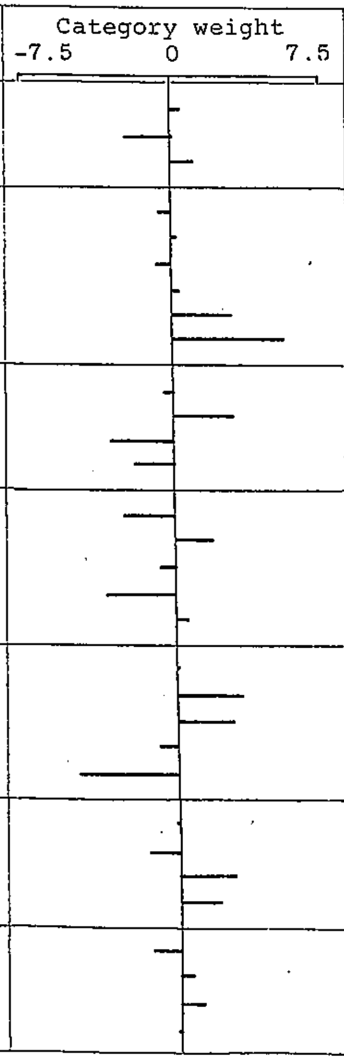
The degree of the influence of the factors on pipes, state of ground and ground motion is quantitatively investigated here, employing the multivariate analysis which is often called "the Quantification Theory 1". The factors on pipes consist of the materials and diameter of pipes.

The factors on state of ground consist of the SPT N-value up to 5m in depth, type of soil up to 5m in depth and underground water table which are obtained from the results of the standard penetration test. The factor on ground motion is the estimated peak ground velocity which was proposed by Kameda, Sugito and Goto[5]. Besides these factors, the length of pipe constructed in a mesh is also added as one more factor.

Table 3 shows the result of multivariate analysis. The largest multiple correlation coefficient was obtained in the analysis using such a category classification. In category classification, attention was given to the following points: equally distribution of sample data to each category and regularly classification of categories. Therefore, such category classification set up as the correlation between the damage ratio and each factor, was explained well. Partial correlation

Table 3 Results of multivariate analysis.

| Item | Category | | Category weight (-7.5 … 0 … 7.5) | Partial correlation coefficient |
|---|---|---|---|---|
| Kind of pipes | ACP | 56 | | 0.18390 |
| | CIP | 29 | | |
| | VP | 27 | | |
| Diameter (φ) mm | φ ≦ 50 | 17 | | 0.21584 |
| | 50 < φ ≦ 100 | 48 | | |
| | 100 < φ ≦ 200 | 29 | | |
| | 200 < φ ≦ 300 | 10 | | |
| | 300 < φ ≦ 400 | 4 | | |
| | 400 < φ | 4 | | |
| SPT N-value (N) | 0 ≦ N ≦ 9 | 15 | | 0.30430 |
| | 9 < N ≦ 11 | 48 | | |
| | 11 < N ≦ 13 | 16 | | |
| | 13 < N | 33 | | |
| Type of soil | Silt | 3 | | 0.32125 |
| | Fine sand | 45 | | |
| | Medium sand | 46 | | |
| | Coarse sand | 11 | | |
| | Clay | 7 | | |
| Water table (H) m | 0 ≧ H ≧ -2.0 | 25 | | 0.36720 |
| | -2.0 > H ≧ -2.5 | 22 | | |
| | -2.5 > H ≧ -3.0 | 22 | | |
| | -3.0 > H ≧ -4.5 | 22 | | |
| | -4.5 > H | 21 | | |
| Peak velocity (V) kine | V ≦ 25.0 | 29 | | 0.29208 |
| | 25.0 < V ≦ 27.5 | 48 | | |
| | 27.5 < V ≦ 30.0 | 19 | | |
| | 30.0 < V | 16 | | |
| Total length (ℓ) km | 0 < ℓ ≦ 0.1 | 23 | | 0.15881 |
| | 0.1 < ℓ ≦ 0.3 | 33 | | |
| | 0.3 < ℓ ≦ 0.5 | 26 | | |
| | 0.5 < ℓ | 30 | | |



Multiple correlation coefficient 0.58779 coefficient reveals the degree of influence of each item on the damage ratio. It can be seen in Table 3 that the partial correlation coefficient for the items on underground water table is maximum in all items, and that the type of soil and SPT N-value up to 5m in depth are larger than other items. It is interesting to note that all items on the state of ground have a great influence on the damage ratio. On the other hand, the partial correlation coefficient of such items as the total length of pipe in a mesh and materials of pipe is small. It is conceivable that the load due to the earthquake could exceed the resistance of the strongest material of pipe, and the severe damage could be caused irrespective of the materials of pipe. Category weight expresses the degree of influence of each category in an item on the damage ratio. This means that the larger this value is, the greater influence the category has on the damage ratio. As in Table 3, the category of 2m to 3m, that of fine sand and that of 9 to 11 are the largest of all categories in the item on the underground water table, type of soil and SPT N-value up to 5m in depth, respectively. They coincide with the relationship between the damage ratio and each item as mentioned in the previous section. These results suggest the correlation between the soil liquefaction and damage to buried pipes. As to the diameter of pipes, the damage of pipes with large diameter affects the results.

The estimated peak ground velocity, however, explains not only the ground motion but also the state of ground. Cramer's coefficient of contingency between the estimated peak ground velocity and SPT N-value up to 5m in depth is 0.70. As this means that the correlation between them is great, the analysis without the item on the estimated peak ground velocity is conducted. The results are similar to the former results. That is, the items on the state of ground indicate large partial correlation coefficients.

As revealed above, it is confirmed that the items on the state of ground, i. e. the underground water table, type of soil and SPT N-value up to 5m in depth, have a great influence on the earthquake damage to the buried pipes. It is interesting to note that the influence of the underground water table which is not given much attention is great. It is also suggested that the soil liquefaction has a great influence on the earthquake damage to the buried pipelines.

## 4. Discussions

Since the damage ratio of the cast iron pipes with large diameter of 400mm and 450mm was high as shown in the previous section, these damage is discussed in detail here. The place of the concentrated damage of the cast iron pipes with 400mm and 450mm diameter is displayed in Fig. 6. These pipes are located in liquefied zone near the boundary between the liquefied and non-liquefied areas. These ground conditions are accordance with the conditions of the experiments which were conducted in Ref. 6). Ref. 6) experimentally investigated on the strain characteristics of the buried pipe fixed at one end during liquefaction. Figs. 9 and 10 show the distribution of the maximum accumulated residual strains of the model pipe and that of mean vibrating strains, respectively, which are the experimental results in Ref. 6). The shaded portions in these figures indicate the improved model ground by compaction, that is, non-liquefied area. It can be seen in these figures that the both pipe strains are maximum value in the liquefied ground near the

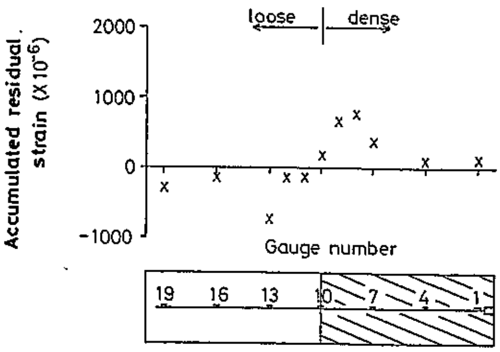



Fig. 9 Distribution of maximum accumulated residual strains of pipe (after Kitaura and Miyajima, 1983[6]).

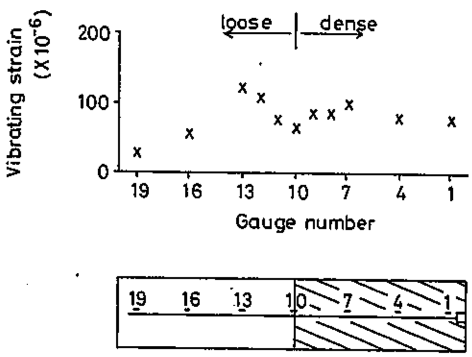



Fig. 10 Distribution of mean vibrating strains of pipe (after Kitaura and Miyajima, 1983[6]).

boundary between liquefied and non-liquefied areas. The greatest similarity can be seen in a comparison of the damage due to liquefaction and the experimental results.

On the other hand, the reasons why the pipes with relatively large diameter of 400mm and 450mm are severely damaged are considered as follows. In general, the weight per unit volume of a water supply pipe filled with water is known to be lighter than that of liquefied soil. And the larger the diameter of pipe is, the larger the difference between them is, that is, the buoyancy acting on the pipe becomes larger. The area moment of inertia of the pipe increases with the increase in the diameter of pipe, that is, the strength of pipe increases. It is, however, conceivable that the strength of joint could not increase propotionately. Therefore, it is suggested that the damage at joint of the pipe with large diameter is related to the buoyancy in liquefaction process.

As shown above, it is now apparent that the probability of failure of pipelines is high, when the pipelines lie across the boundary ground between the liquefied and non-liquefied area. Care should be taken of the influence of the buoyancy on the pipelines with large diameter in liquefaction process.

## 5. Concluding Remarks

Conclusions obtained from the present study are summarized as follows;

1) It becomes evident from the investigation by the record of the earthquake damage that the damage to pipelines is strongly influenced by the state of ground, especially soil liquefaction.
2) The results of the multivariate analysis quantitatively shows that the underground water table, type of soil and SPT N-value up to 5m in depth have a great influence on the earthquake damage to the buried pipes.
3) The probability of failure of pipelines is high, which pass the boundary ground between liquefied area and non-liquefied area.
4) Care should be taken of the influence of the buoyancy on the pipelines with large diameter in liquefaction process.

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