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Quantitative analyses on liquefaction induced permanent ground displacement and its effects on earthquake damage

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ABSTRACT: The factors influencing the magnitude of the liquefaction induced permanent ground displacements are quantitatively analyzed and a formula for evaluating the permanent ground displacement is proposed. Furthermore, the correlation of the damage rate to houses, buried pipes, etc., with the permanent ground displacements as well as with the permanent ground strains, which are calculated from the measured displacements, is discussed.

1 INTRODUCTION

The authors conducted measurement of permanent ground displacements in Noshiro City caused by the 1983 Nihonkai-Chubu and in Niigata City the 1964 Niigata earthquakes by pre- and post-earthquake aerial survey and reported that the maximum horizontal displacement reached over 5 m and 8 m during these two earthquakes, respectively. Furthermore it was clarified that the permanent ground displacements were caused by soil liquefaction.

In this paper the factors influencing the magnitude of the displacements and the correlation of the damage to houses, buried pipes with the ground displacements and ground strains are discussed.

The analysis in this paper includes the data of permanent ground displacements by the 1971 San Fernando earthquake in addition to the data by the above-mentioned two earthquakes. The permanent ground displacements that occurred in the vicinity of the Upper Van Norman Lake during the San Fernando earthquake were studied by O'Rourke and Youd.

2 STUDY OF FACTORS INFLUENCING MAGNITUDES OF PERMANENT GROUND DISPLACEMENTS

The following factors, shown in Fig. 1, were considered for the analysis on the correlation between the magnitude of the ground displacement, and the geological and topographical conditions:

(i) Thickness of liquefied soil layer.
(ii) Gradient of ground surface.
(iii) Gradient of liquefied layer (gradient of upper and lower boundary faces of liquefied layer).
(iv) Depth of liquefied soil layer (depth of upper and lower boundary faces of liquefied layer).

The subsurface soil condition was surveyed along the section lines drawn approximately parallel to the horizontal displacement vectors. Some examples of section lines in the northern part of Noshiro City is shown in Fig. 2.

The liquefied soil layer was conjectured by the Factor of Liquefaction Resistance F_L proposed by Iwasaki et al.* The soil layer with F_L less than 1.0 was considered to have been liquefied.

These factors were determined from each soil layer profile according to the following procedure.

(i) The established sections were divided into segments as shown in Fig. 1, by taking into account the gradient of the ground surface, the distribution pattern of the permanent ground displacements, and the topographical conditions. Each segment represents the area where the sliding of the ground can be regarded as one block.

* The Liquefaction Resistance Factor, F_L was proposed by Iwasaki et al, showing the degree of the liquefaction.

(ii) The factors concerning the conditions of the liquefied soil layer and the magnitudes of the permanent ground displacements were determined as the mean values of each segment.

(iii) In the case that the estimated liquefied zone was divided into more than one layer, the thickness of the intermediate layers was also added to the total thickness, as shown in Fig. 1, because these layers actually have a high probability of being liquefied by the effect of the surrounding layers.

(iv) The magnitudes of the permanent ground displacements along the Shinano River were considered to be largely dependent on the existence of the revetment, where the ground surface had an abrupt vertical discontinuity. Therefore, in this case, the gradient of the ground surface was tentatively determined as the ratio of the horizontal distance of the segment to the depth of the river bed, as shown in Fig. 1 (b).

Fig. 3 shows the relationship between the gradient of the ground surface and the magnitudes of the permanent ground displacements. Although there are some contradictions among the data obtained from the three earthquakes, it can be concluded that larger the gradient of the ground surface, the larger the magnitudes of the permanent ground displacements.

The permanent ground displacements along the Shinano River (4 plots in the figure with a gradient of above 3%) are somewhat larger, compared with the displacements caused by the other two earthquakes. It can be considered that the topographical condition, the vertical discontinuity of the ground surface at the revetment, largely influenced the magnitude of the displacements.

Fig. 4 shows the relationship between the gradient of the liquefied layer's lower boundary face and the magnitude of the permanent ground displacements. In the case of the Niigata earthquake, the magnitude of displacement shows some correlation with the gradient, but no apparent correlation can be found for the Nihonkai-Chubu earthquake (shown as Noshiro in the figure). The reason for this may be due to the fact that most of the liquefied layer's lower boundary face in Noshiro is nearly horizontal and the magnitude of the displacements were mainly governed by the gradient of the ground surface.

Fig. 5 shows the relationship between the displacements and the gradient of the liquefied layer's upper boundary face, but no clear relationship can be found.

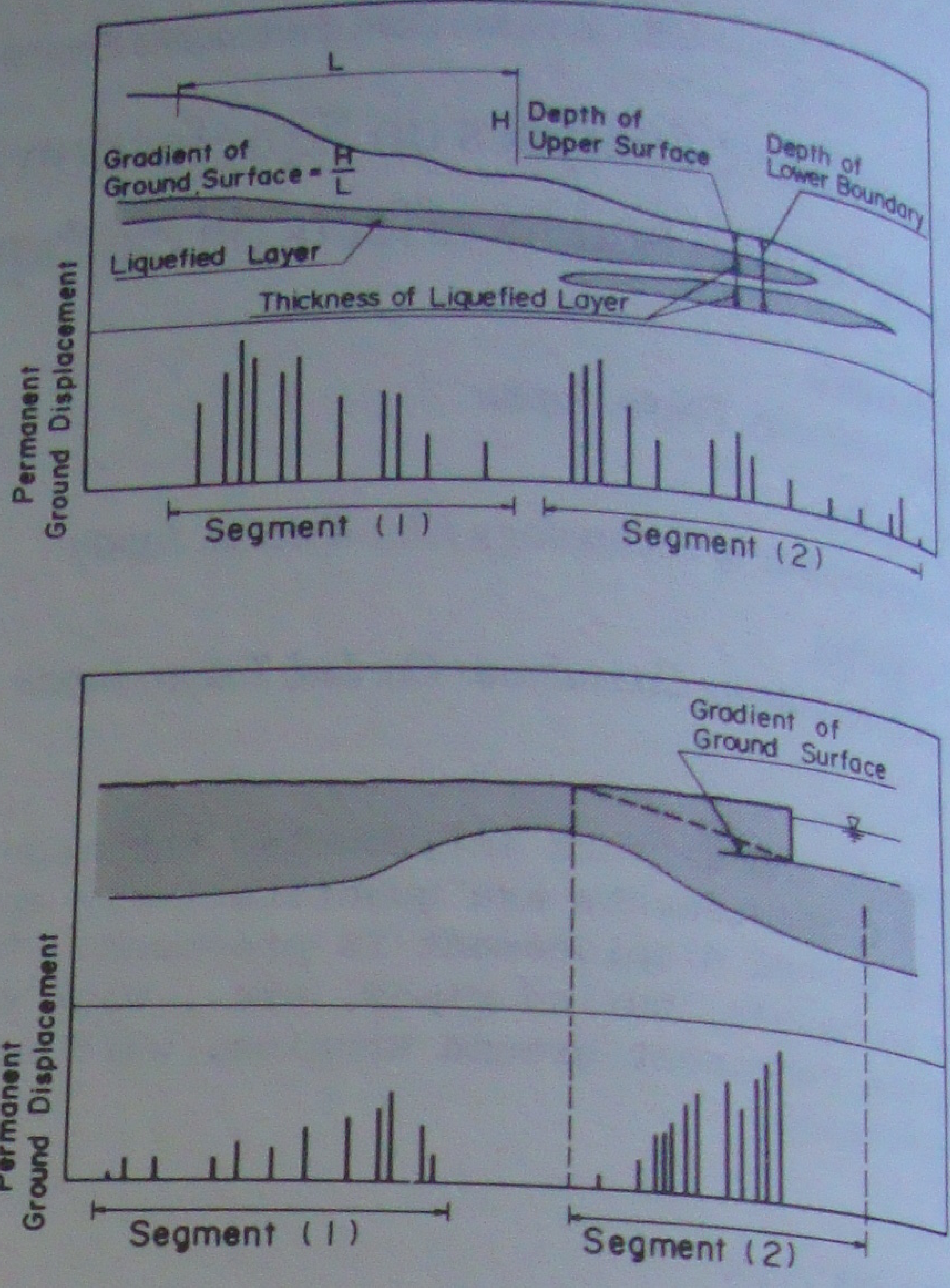

Fig. 1 Factors of liquefied soil layer condition and topography

Fig. 2 Sector lines for the survey of soil condition in northern part of Noshiro City

As mentioned thus far, it was discovered that the gradient of the ground surface and that of the liquefied layer's lower boundary face had a relatively high correlation with the magnitude of the permanent ground displacements. However, neither one of these two parameters can be considered to be commonly influential to the displacements by both earthquakes, because there are differences in the types of the permanent ground displacements.

Fig. 6 shows the relationship of the permanent ground displacements with the larger values of the ground surface gradient or the lower boundary face gradient. A better correlation is found with the displacements compared with the results shown in Figs. 3 and 4 and it can be considered that the larger gradients of the ground surface or the lower boundary face are a more proper parameter explaining the magnitude of the permanent ground displacements.

Fig. 7 shows that the correlation of the magnitude of the permanent ground displacements with the thickness of the liquefied layer is comparatively high and therefore it can be concluded that the thickness is one of the factors governing the magnitude of permanent ground displacements.

Besides the above-mentioned factors, the correlation of the depth of liquefied soil layer and the Factor of Liquefaction Resistance F_L as an index showing the degree of liquefaction was examined, but no clear correlation could be found.

3 REGRESSION ANALYSIS OF MAGNITUDES OF PERMANENT GROUND DISPLACEMENTS

From the above discussion, it was established that the thickness of the liquefied layer and the larger gradient of the ground surface or the lower boundary face of the liquefied layer had a comparatively close correlation with the permanent ground displacement.

Based on the data obtained from the 1983 Nihonkai-Chubu, the 1969 Niigata, and the 1973 San Fernando earthquakes, the total number of which were about 60, the following regression formula for the evaluation of the permanent ground displacements was established.

$$D = 0.75 \cdot \sqrt{H} \cdot \sqrt[3]{\theta}$$

where,

D: Permanent ground displacement in the horizontal direction (m)

H: Thickness of the liquefied layer (m)

θ: The larger gradient of the ground surface or the lower boundary face of the liquefied layer (%)

Fig. 8 shows a comparison between the permanent ground displacements estimated by the above formula and the measured values. Most of the data are within the two dotted lines in the figure which show the range in which the estimated displacements are 1/2 to twice the measured values.

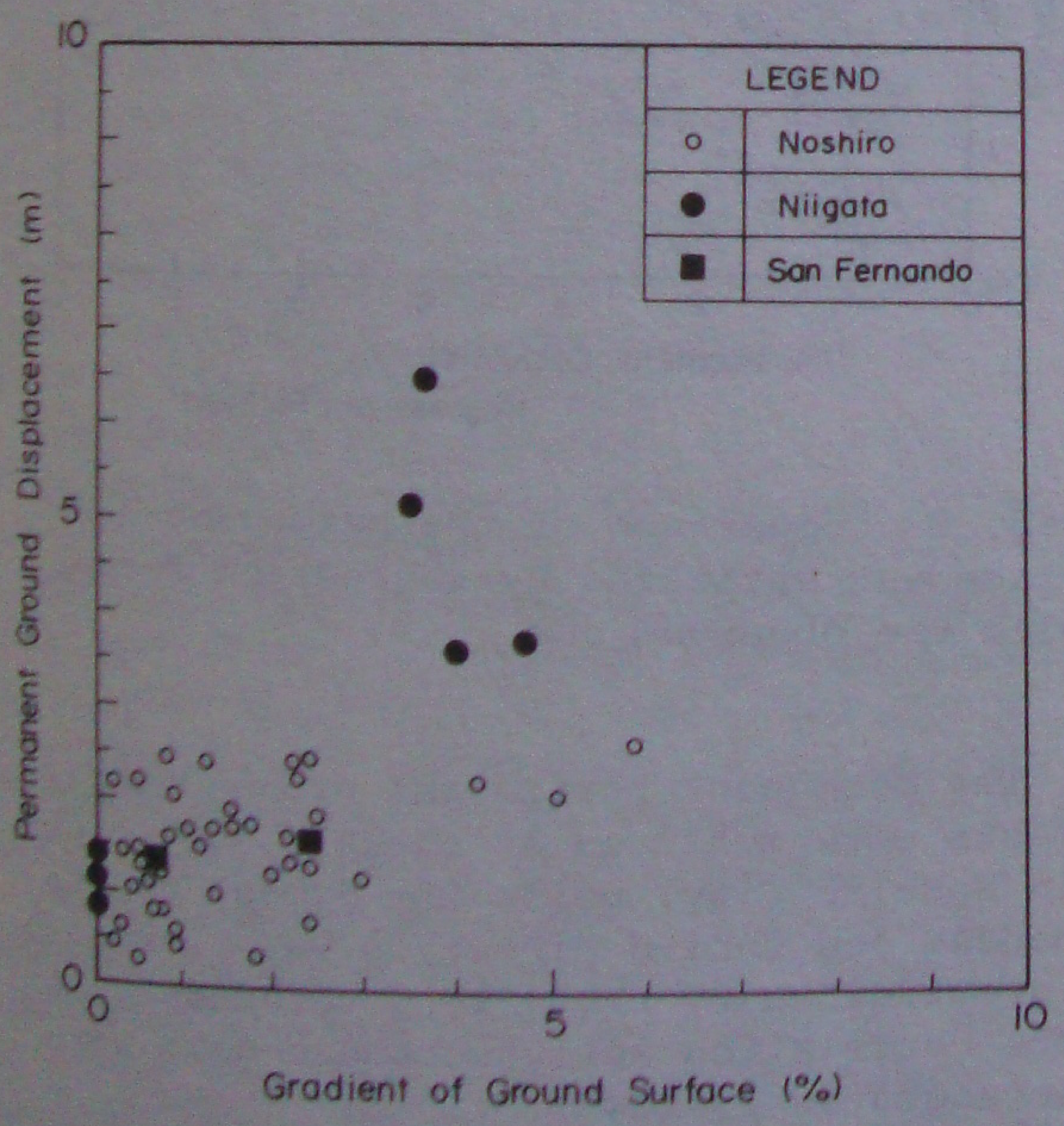

Fig. 3 Relationship between the gradient of ground surface and the magnitude of permanent ground displacement

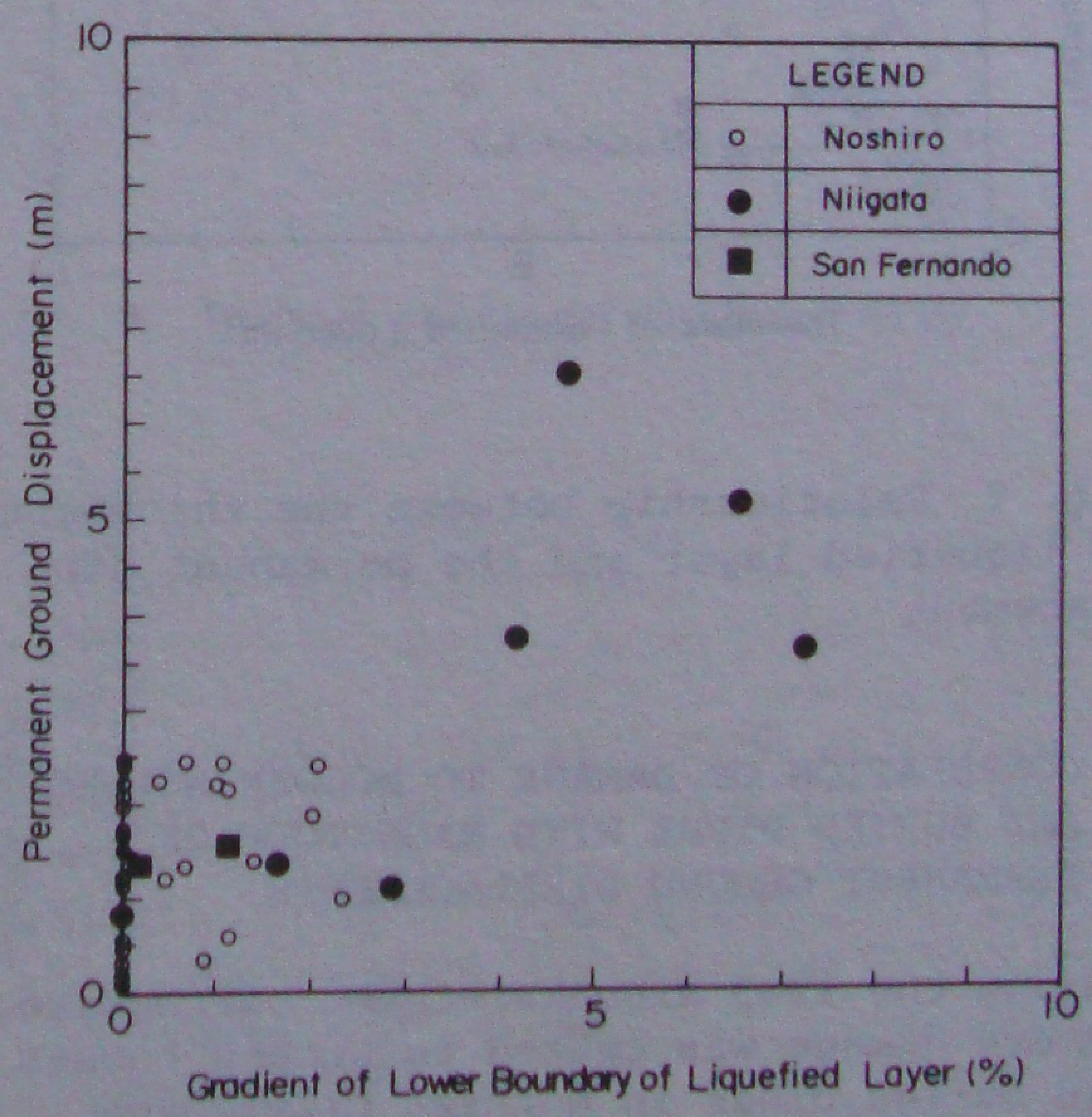

Fig. 4 Relationship between the gradient of lower boundary face of liquefied layer and the permanent displacement

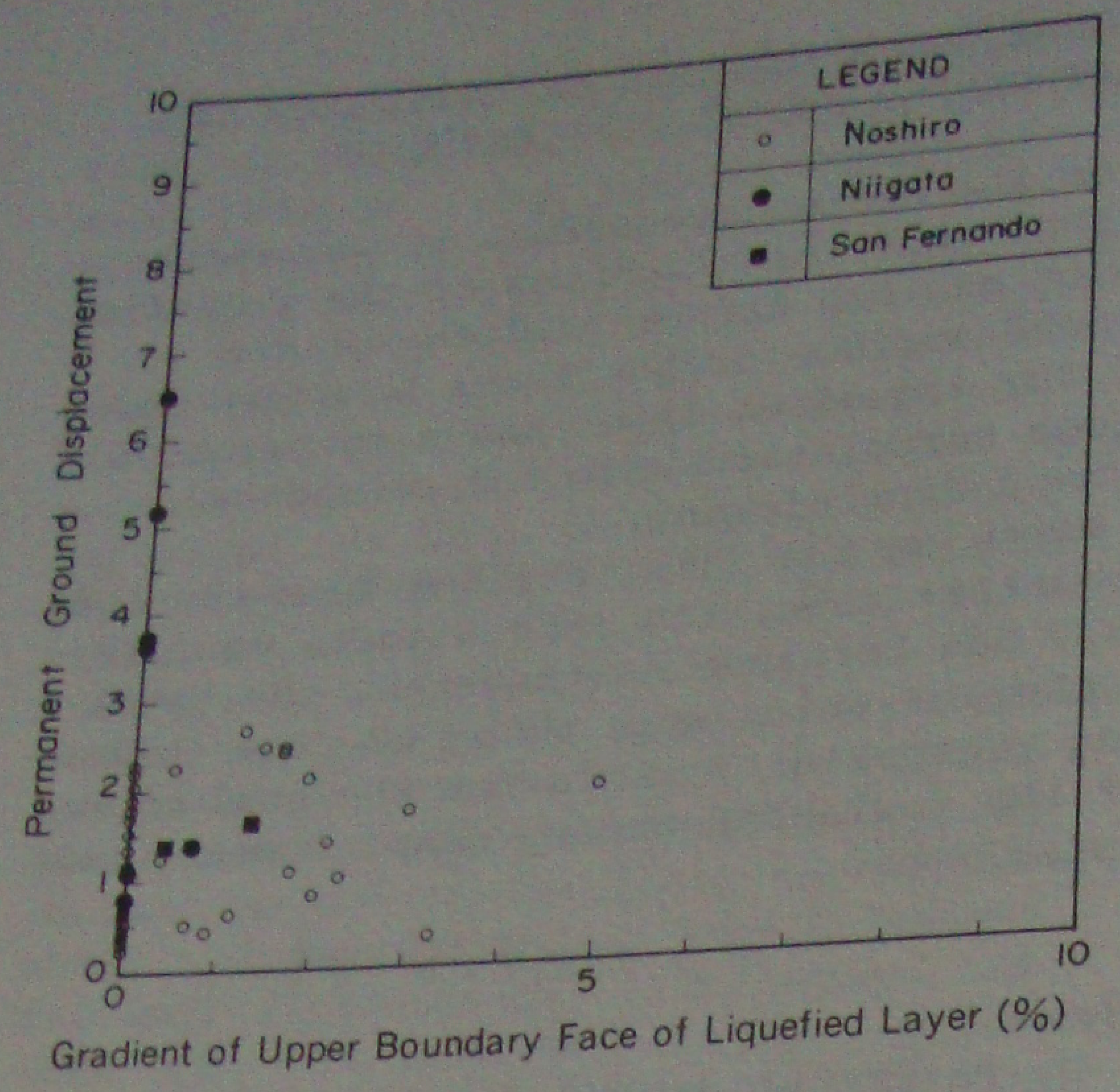

Fig. 5 Relationship between the gradient of upper boundary face of liquefied layer and the permanent displacement

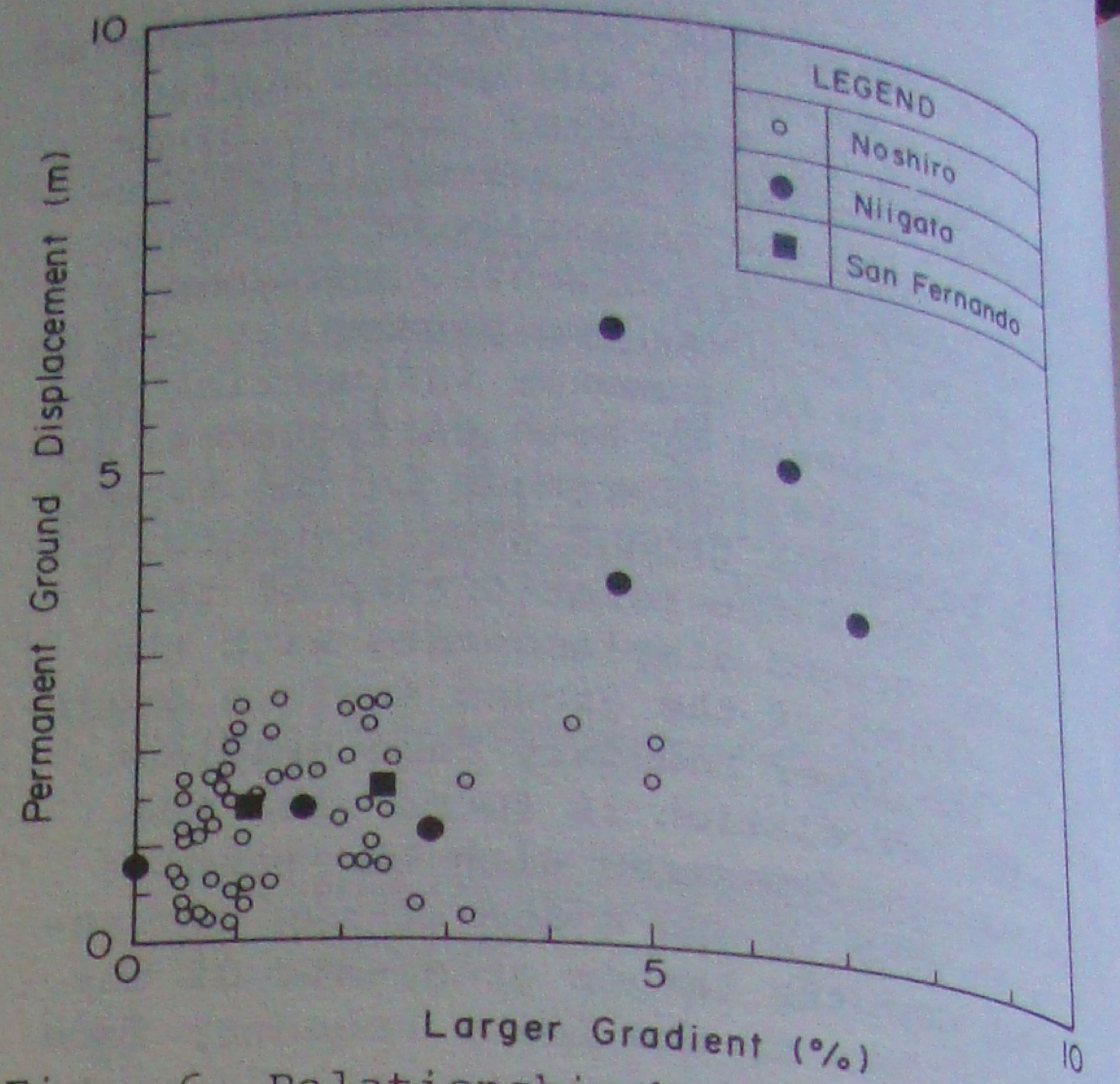

Fig. 6 Relationship between the larger value of the ground surface gradient or the lower boundary face gradient, and the permanent displacement

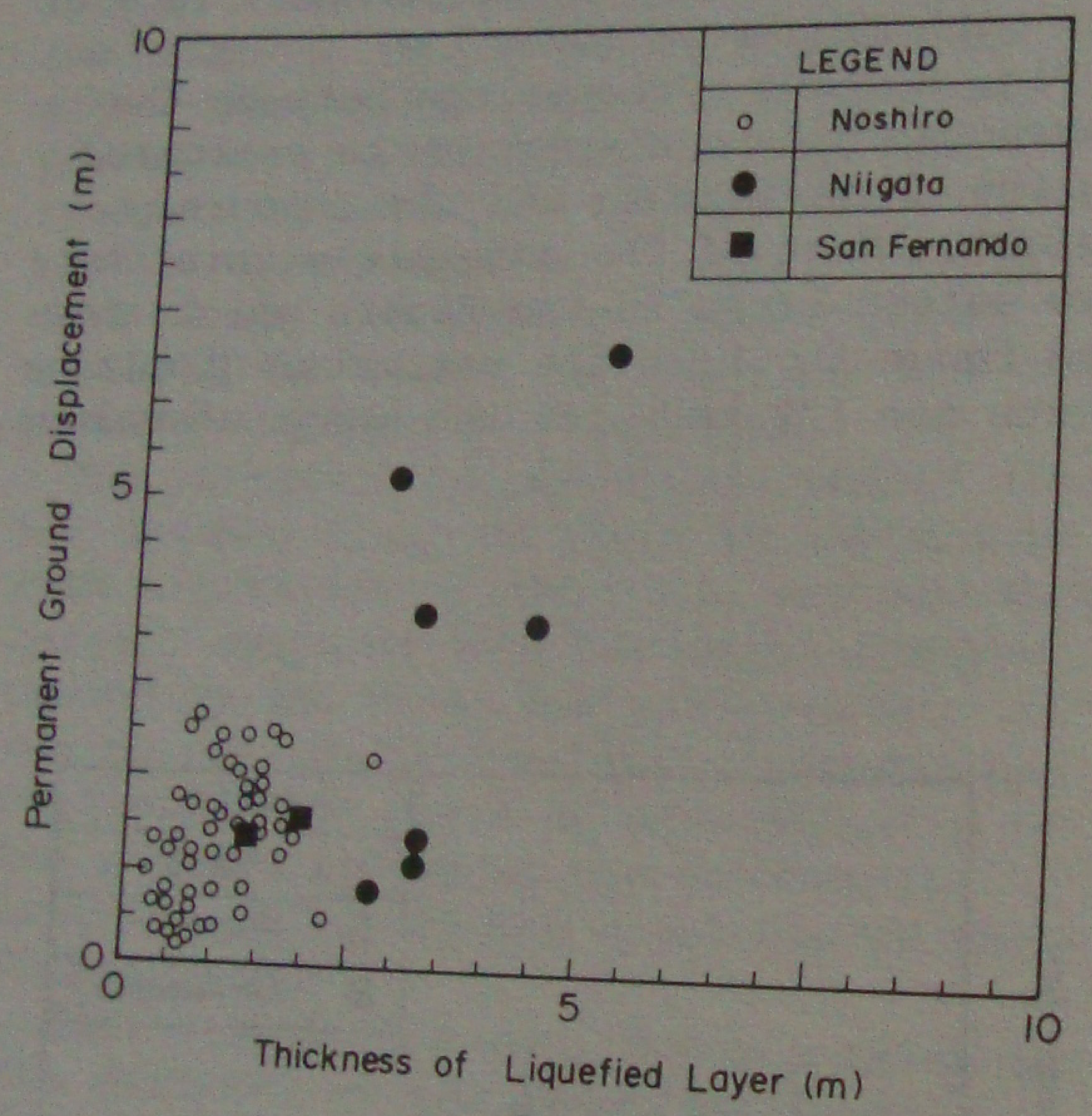

Fig. 7 Relationship between the thickness of liquefied layer and the permanent displacement

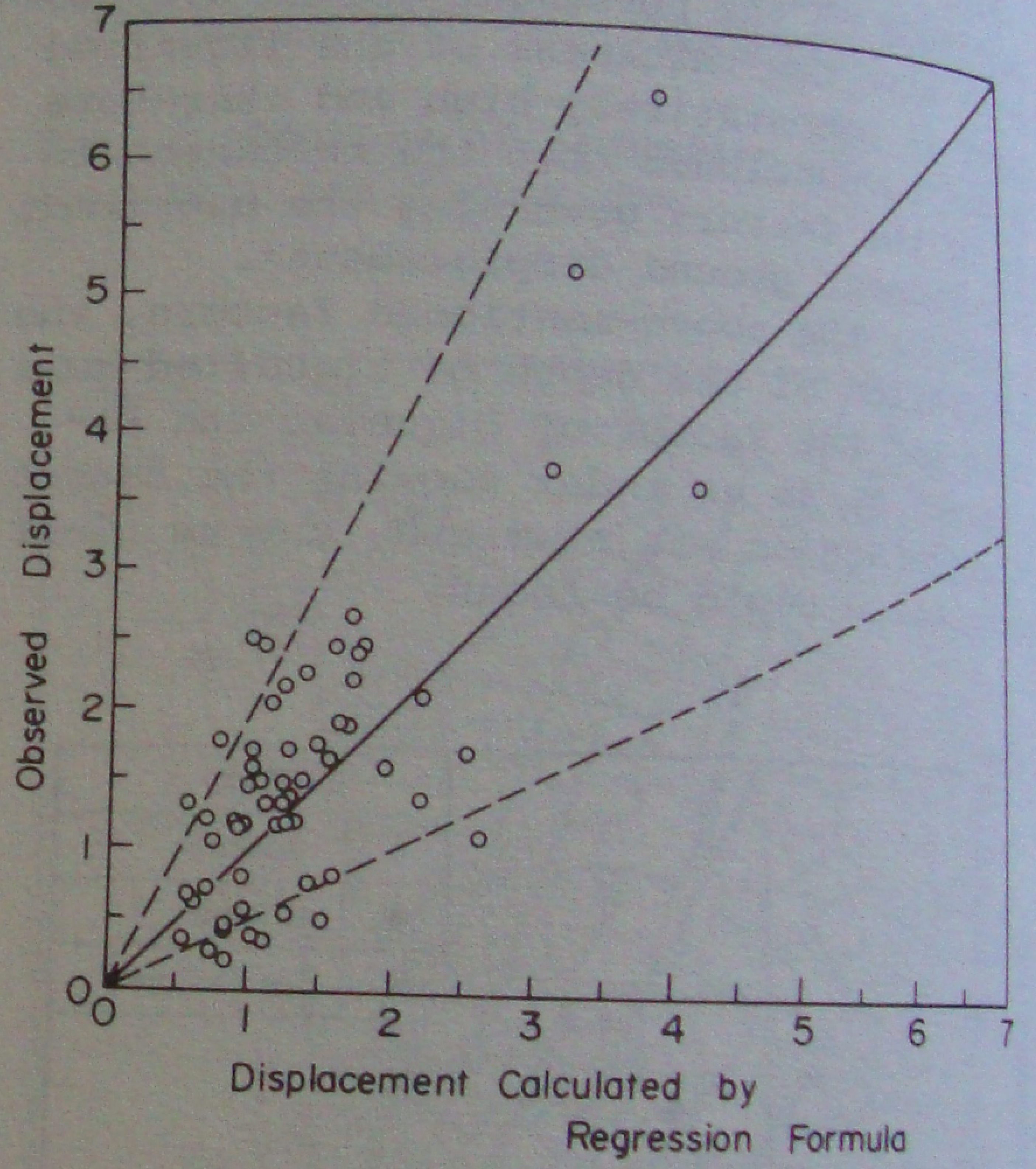

Fig. 8 Comparison of the permanent displacement estimated by regression formula with the observed one

4 CORRELATION OF DAMAGE TO WOODEN HOUSES AND BURIED PIPES WITH MAGNITUDE OF PERMANENT GROUND DISPLACEMENTS

During the 1983 Nihonkai-Chubu earthquake, severe damage was caused to wooden houses and buried pipes in Noshiro City. The correlation between the magnitude of permanent ground displacements and the damage rate to wooden houses and buried pipes is examined.

The permanent horizontal ground displacements were measured at about 2,000 points in Noshiro City, while the damage to the houses and buried pipelines was thoroughly investigated by the city government. For the correlation analysis these data were arranged as follows:

(i) The area of Noshiro City, where the permanent ground displacements were measured, was divided into 100 m square cells, as shown in Fig. 9. The mean value of the absolute amplitudes of the permanent ground displacements measured within each cell was calculated, disregarding the directions of the displacement vectors.

(ii) In cases in which the amplitudes and directions of displacement vectors in the adjacent cells are similar, they were combined to form one block, from which one mean value of the ground displacements was calculated. The reason for this was that by doing so the number of samples of damage to houses and buried pipes, included in one block would be increased, thereby improving the reliability of the results of the correlative analysis between the damage rate and the permanent ground displacements.

(iii) The rate of damage to buried pipes was calculated as a number of damage points per one km in each cell or block, and the rate of damage to houses was obtained as a ratio of the number of damaged houses to the total number of houses, as shown in the following:

$$\text{Rate of damage to houses} = \frac{n_1 + 0.5n_2}{N}$$

where,

N: Total number of houses in each cell or block

n_1: Number of totally destroyed houses in each cell or block

n_2: Number of partially destroyed houses in each cell an block

The relationship between the rate of damage to houses and the magnitudes of the permanent ground displacements is shown in Fig. 10. A certain high correlation can be recognized between the displacement magnitude and the damage rate to houses, however, it should be noted that in some area, even though the permanent displacement is small, the damage rate is comparatively high.

For example, the asterisk (*) in the figure shows the damage rate at one block in the northern part of the city. In this area, the permanent ground displacement was small, but ground failures such as cracks, sand boiling, etc. were found. This means that the houses can be damaged by local failures of the foundation ground without large displacement of ground.

Fig. 11 shows the damage rates to cast iron gas pipes (CIP) and steel gas pipes (SP) with diameters of 75 to 150 mm. A definite conclusion could not be reached because of an insufficient number of data, but it is clear that the damage rates to both types of pipes have a proportionsl relationship with the magnitudes of permanent ground displacements. It can also be seen from the figures that the damage rate to CIP is 2 or 3 times that of SP.

It should be noted that in some areas where the permanent ground displacements were small, the damage rate to CIP is very high. For example, the asterisk (*) in the figure indicates an area where the

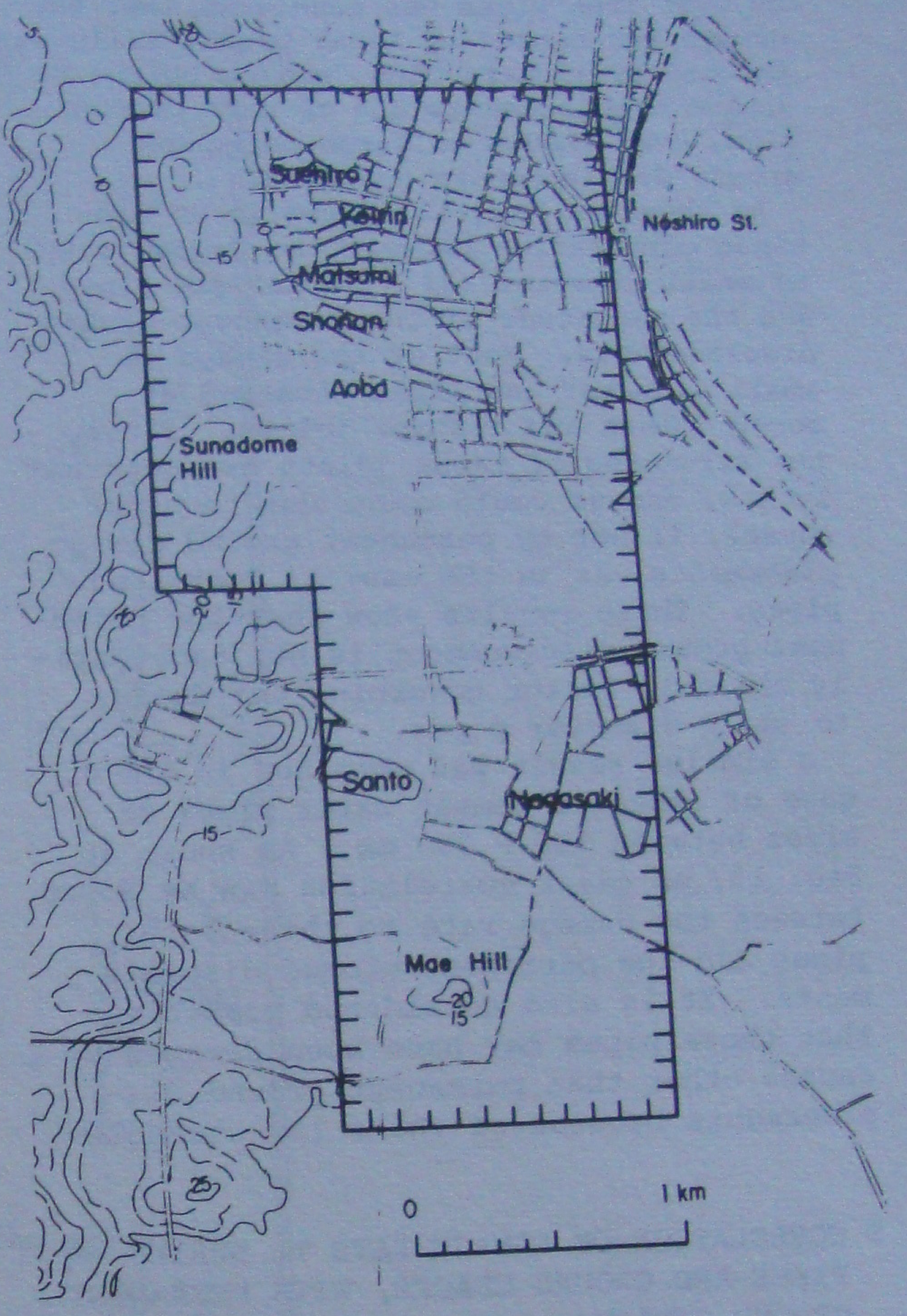

Fig. 9 Square cells in Noshiro City

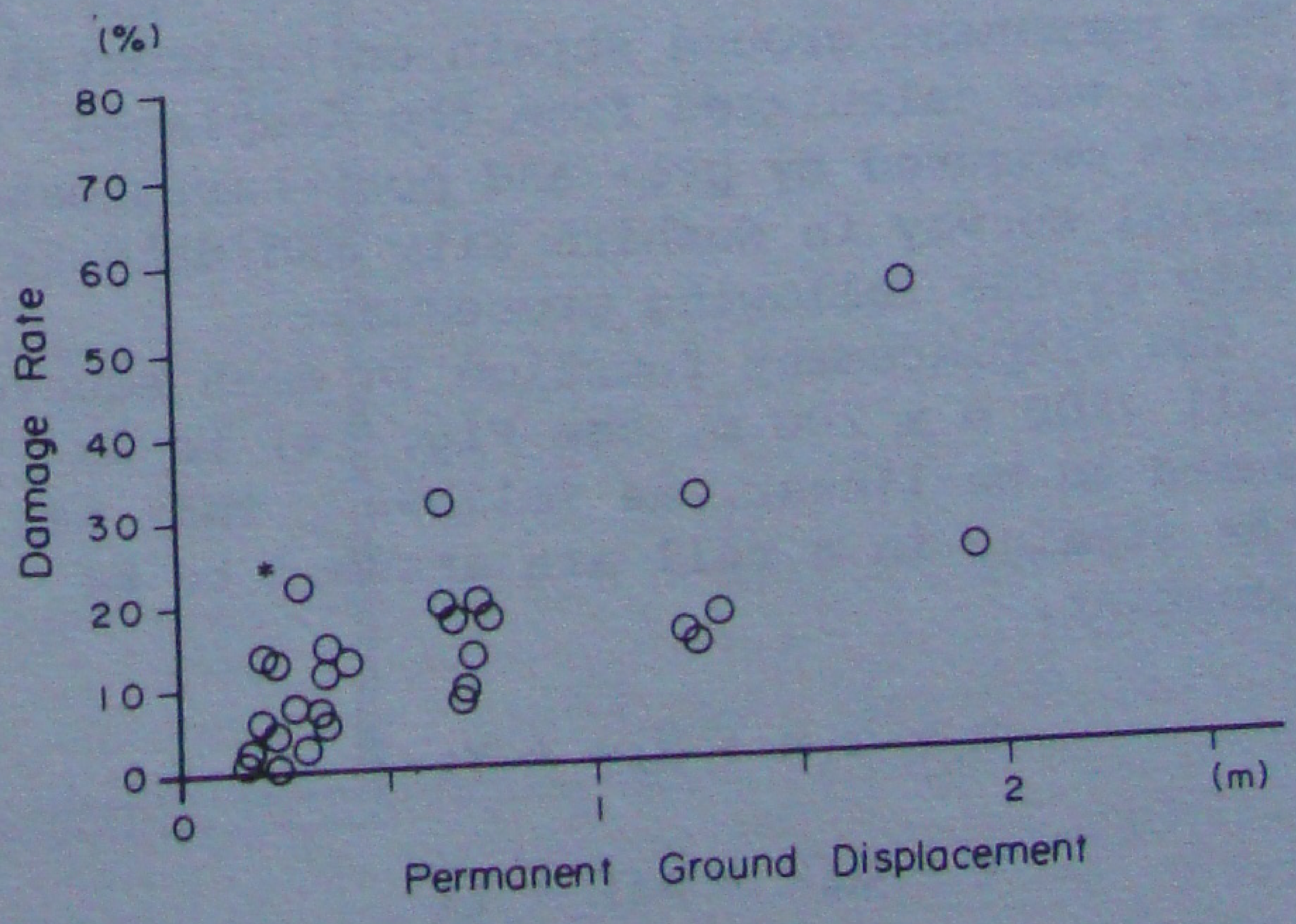

Fig. 10 Relationship between the damage rate to wooden houses and the permanent displacements

damage rate was very high, about 50 instances per km, even though the permanent ground displacements were small, less than 25 cm. In this area many ground failures such as cracks, subsidence and risings due to liquefaction were observed. This indicates that because the strength of cast iron pipes was generally low, the damage was caused by local ground failures induced by liquefaction, and/or by the relative displacements due to wave propagation, even though no large permanent ground displacements occurred.

As shown in Fig. 12, there is no distinct correlation between the damage rate to small diameter (32 - 50 mm) gas pipes and the magnitude of the permanent ground displacements. Most of the damage to small diameter gas pipes occurred at screw joints and T-shape joints. Since the strengths of these joints are generally low, damage could occur due to other causes, if not by permanent ground displacements, as in the case of cast iron pipes. These results show that the permanent ground displacement is not necessarily the only factor governing the damage to small diameter pipes.

A similar result was obtained in the case of asbestos cement water pipes of sizes between 100 - 200 mm. As shown in Fig. 13, no clear correlation can be found between the damage rate to these water pipes and the permanent ground displacements. It is also considered possible that these pipes may have been damaged by causes other than permanent ground displacements because of their low strengths.

5 CORRELATION OF DAMAGE RATE TO BURIED PIPES AND GROUND CRACKS, WITH PERMANENT GROUND STRAINS

5.1 Calculation of permanent ground strain

The permanent ground strain on horizontal plane was calculated from the displacements measured by pre- and post-earthquake aerial survey in Noshiro City and Niigata City by the following procedure:

The displacement function in each square cell (200 m x 200 m, see Fig. 14) is assumed to be linear, as follows. That is, the strains in a cell are assumed to be constant.

$$u = \alpha_1 x + \beta_1 y + \gamma_1$$

$$v = \alpha_2 x + \beta_2 y + \gamma_2$$

where,

x, y: Coordinates in the east-west and south-north directions

u, v: Components of ground displacements in the respective directions.

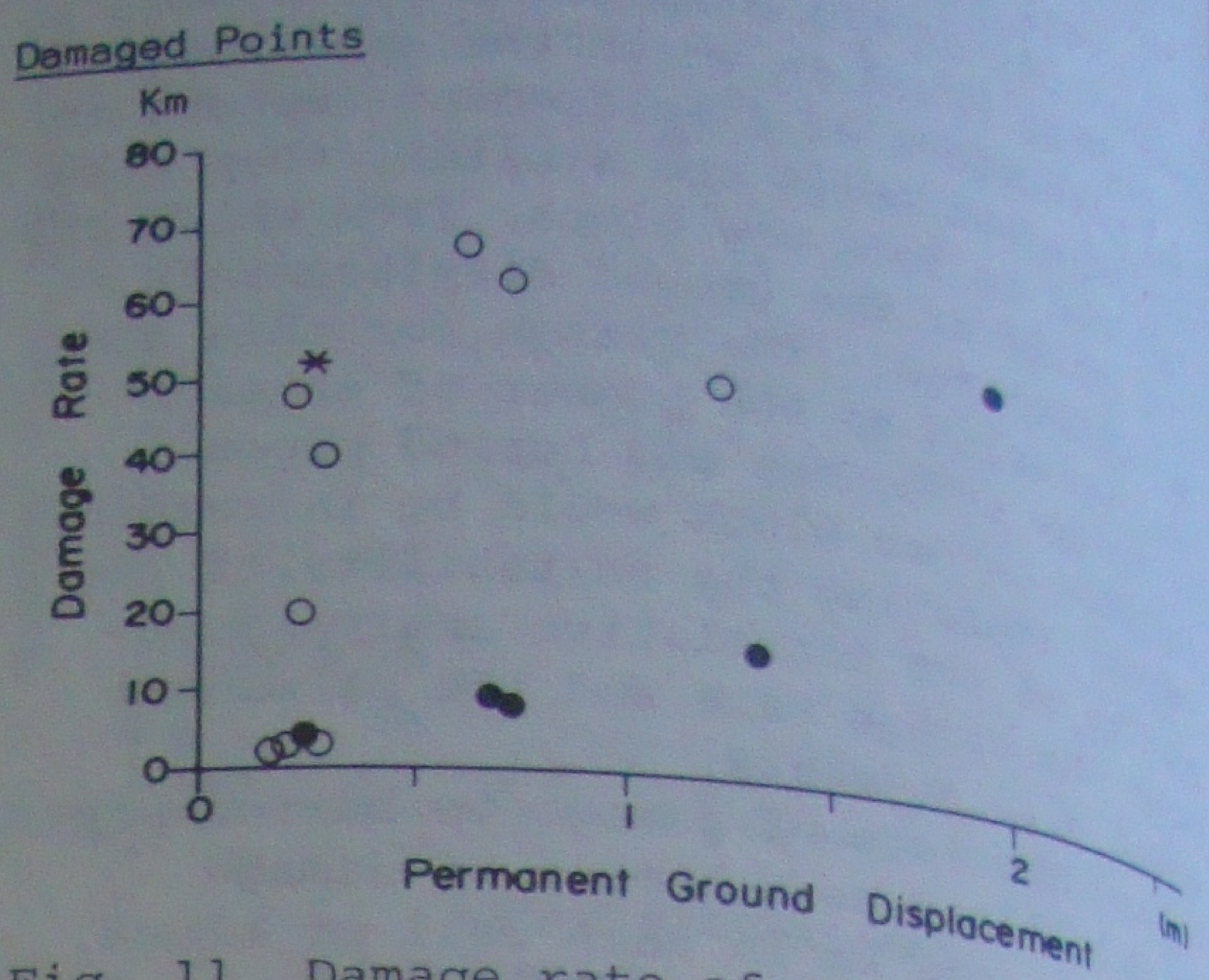

Fig. 11 Damage rate of gas pipe (ø=75 - 150 mm, ● Steel Pipe, ○ Cast Iron Pipe)

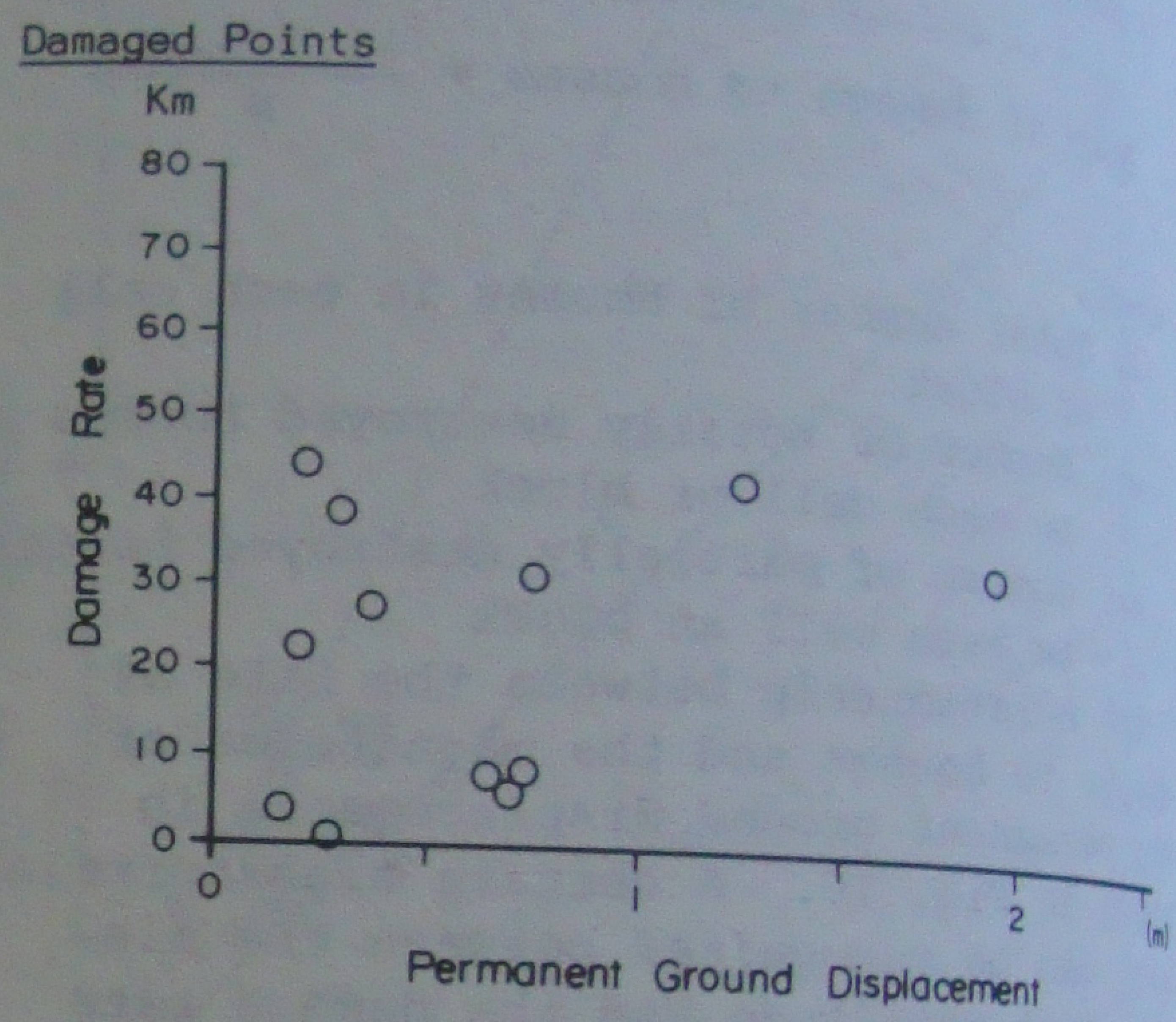

Fig. 12 Damage rate of gas pipe (ø=32 - 50 mm, Steel Pipe)

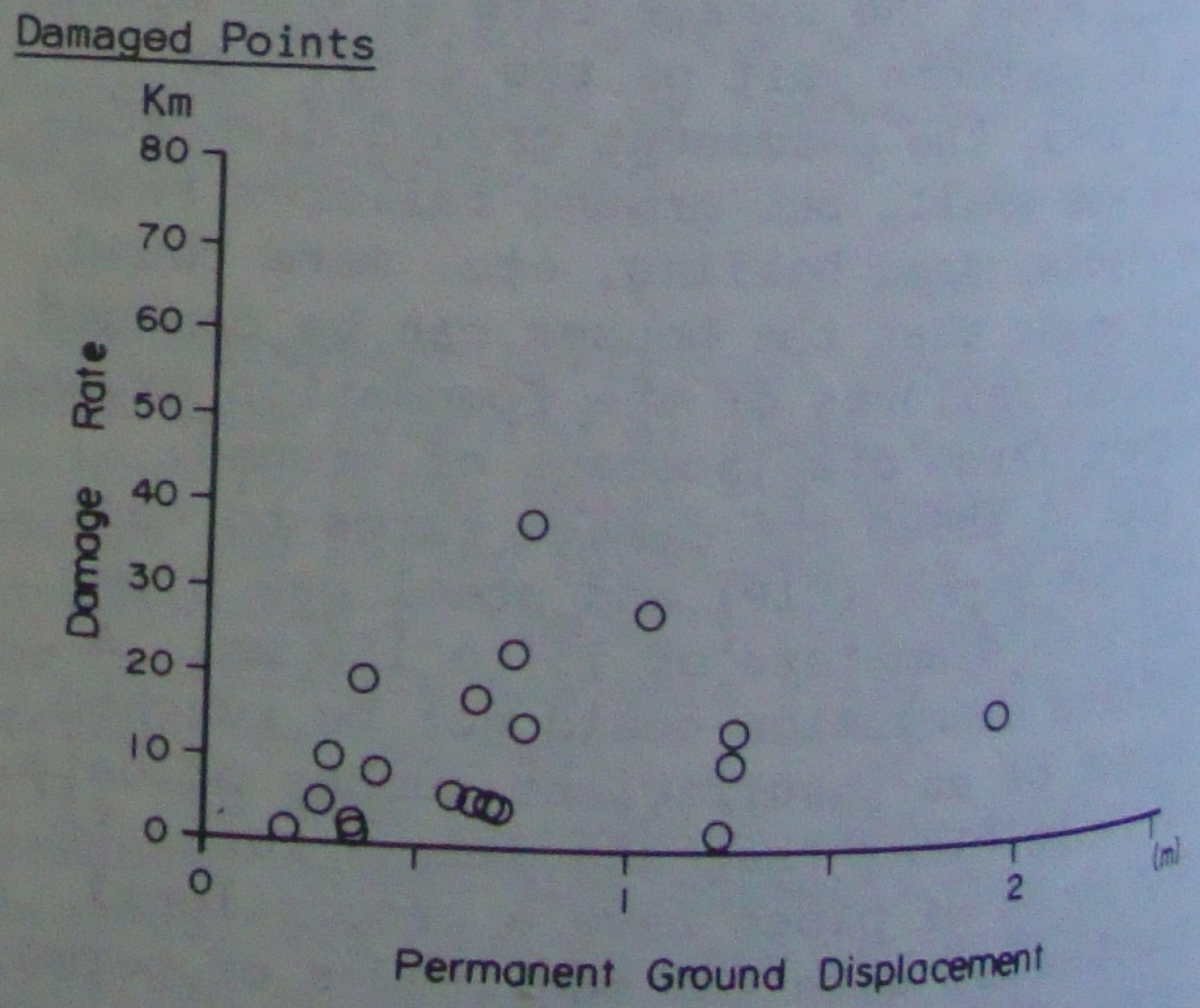

Fig. 13 Damage rate of water pipe (ø=100-200 mm, Asbestos Cement Pipe)

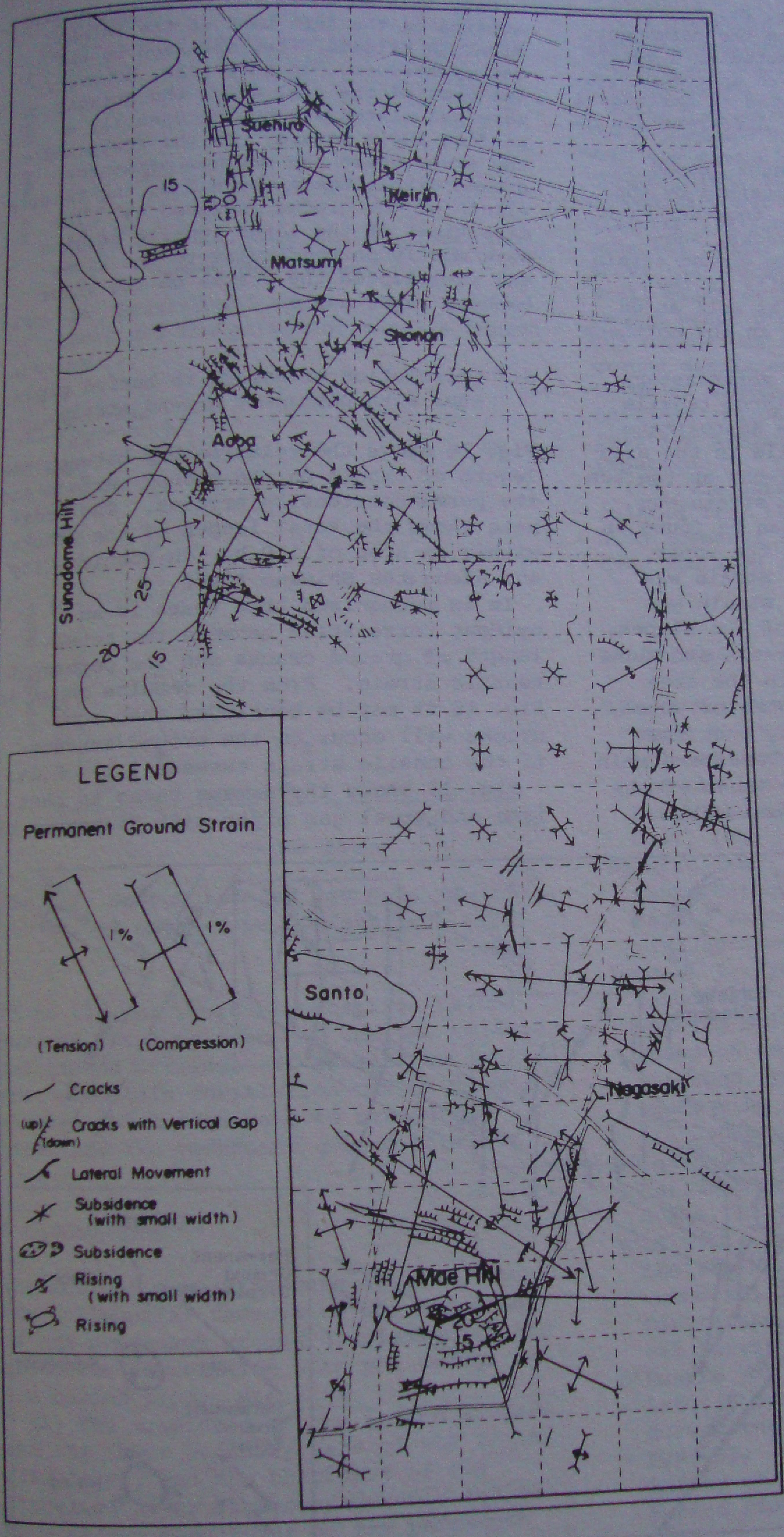

Fig. 14 Permanent ground strain and ground failure in Noshiro City

Six coefficients α_1, α_2, β_1, β_2, γ_1 and γ_2 are determined from the permanent ground displacements measured in a square cell using the least square approximation. The permanent ground strains on horizontal plane are obtained as the differentials of the displacement function.

Fig. 14 shows the permanent ground strains in Noshiro City obtained by the above mentioned procedure, together with ground failures such as cracks, subsidences, etc. The maximum ground strain exceeded 1.5% around Mae Hill in the southern part of the city as well as on the slope of Sunadome Hill in the northern part.

On the upper part of the northeastern slope of Sunadome Hill, a large tensile strain was caused along the approximate direction of the slope, while in the area near Shonan-cho and Matsumi-cho at the toe of the slope, a compressive strain was caused. A similar result can be found on the slopes of Mae Hill. On the upper parts of the slopes tensile strain was dominant, while compressive strain was notable in the lower parts of the slopes.

Ground failures such as cracks and subsidences were concentrated in the area where the permanent ground strains were dominant. It is worth noting that the directions of the principal tensile strain are roughly perpendicular to those of the cracks on the slope of Sunadome Hill.

Fig. 15 also shows the permanent ground strains on the left bank of the Shinano River in Niigata City, obtained by the same procedure. In this case, however, the area of the cell where the strains were calculated was not necessarily a perfect 200 m square. In the Kawagishi-cho area, where the maximum permanent ground displacement was 8.5 m, the tensile strain of the ground exceeded 4%. The directions of the large tensile strains were mostly perpendicular to the river and intersected the cracks on the river bank at right angles.

5.2 Correlation of damage to buried pipes, etc. with permanent ground strain

Fig. 16 shows the relationship between the length of cracks on the ground surface and the permanent tensile strains. The ordinate shows the total length of the cracks within an area of 1.0 ha. in Noshiro City and along the Shinano River.

It is recognized that there is an evident correlation between the total length of ground cracks and the permanent tensile strain. From the results shown in Fig. 16 it may be concluded that some cracks will occur on the ground surface if the tensile strain exceeds 0.1 - 0.2%.

Fig. 17 shows the damage rates to cast iron and steel gas pipes with diameters of

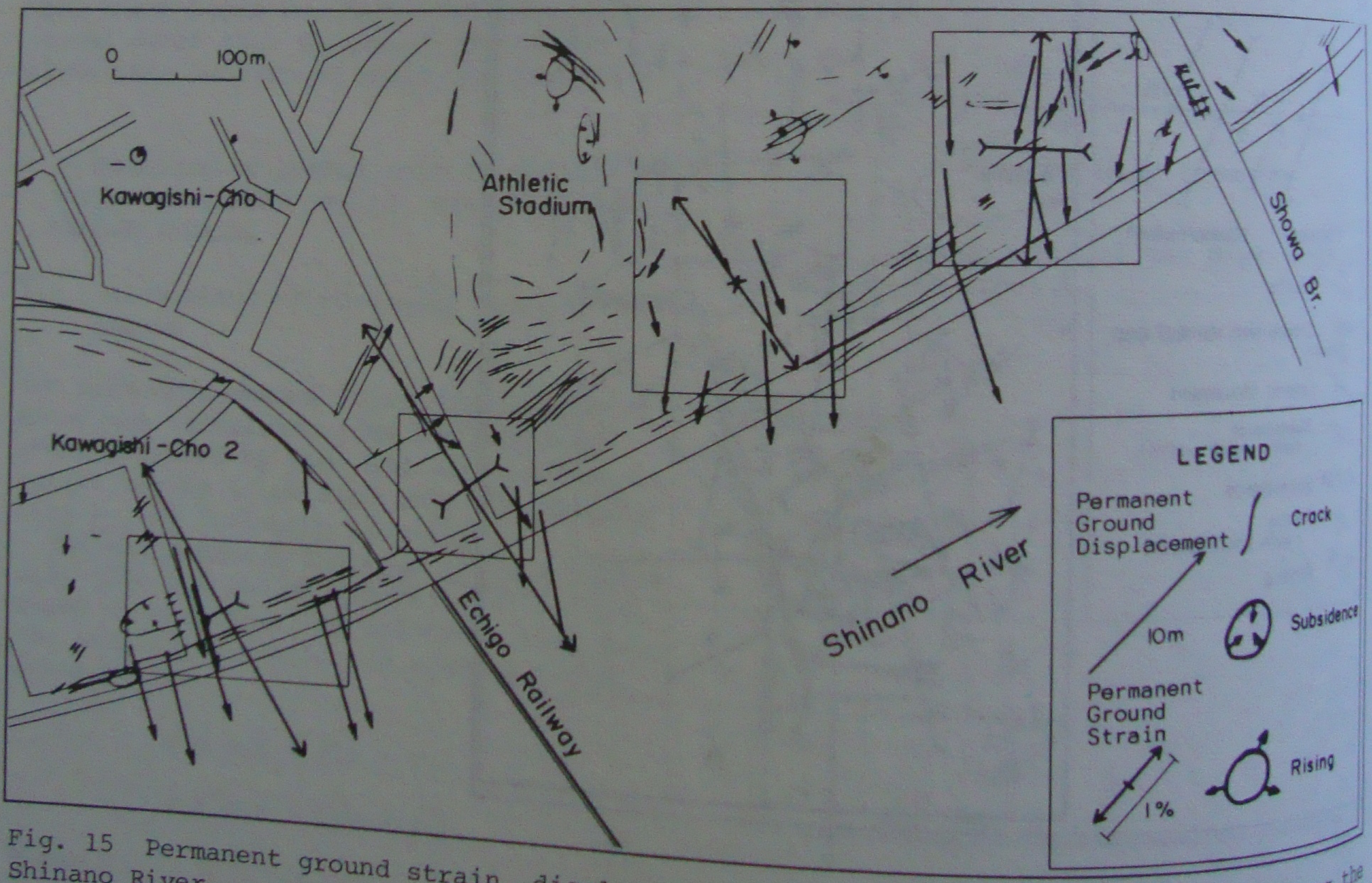

Fig. 15 Permanent ground strain, displacements and ground failure in the area along the Shinano River

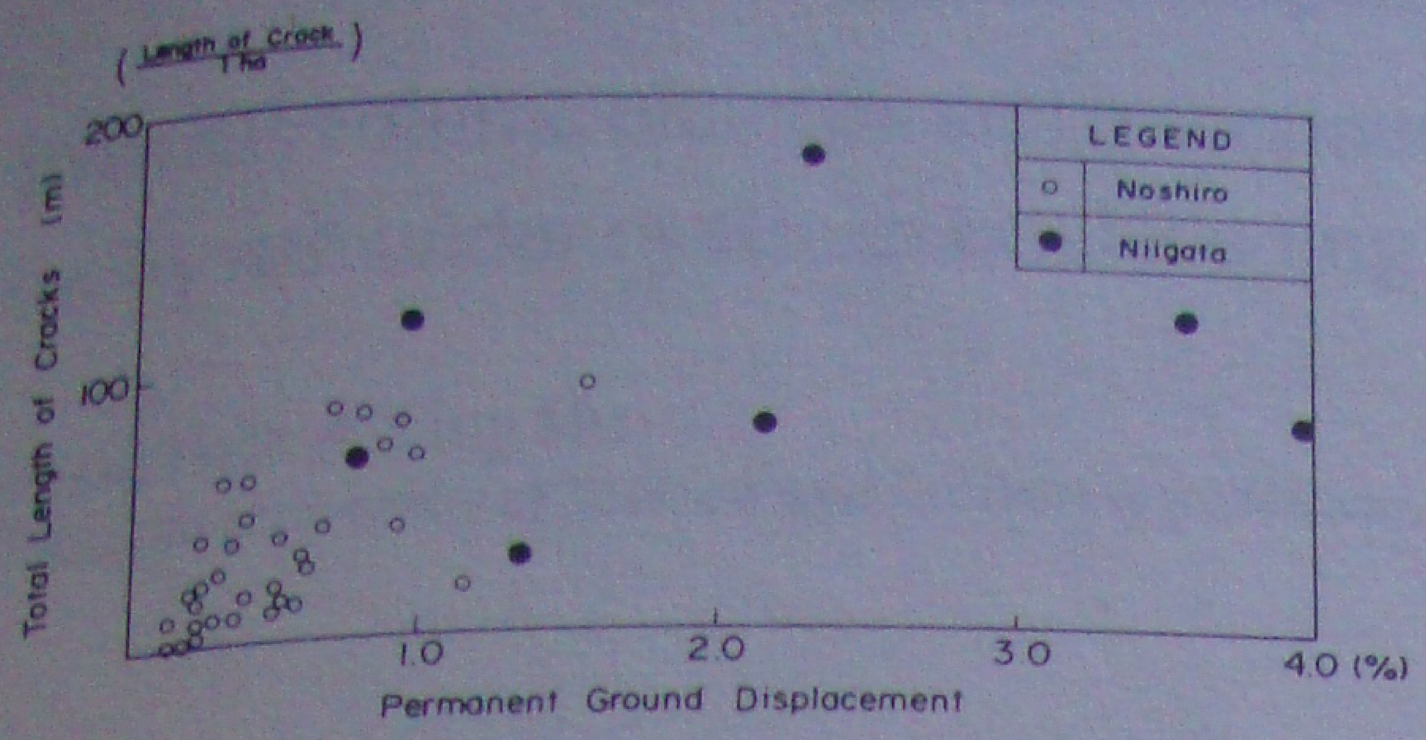

Fig. 16 Relationship between the lengths of cracks and the permanent tensile ground strains

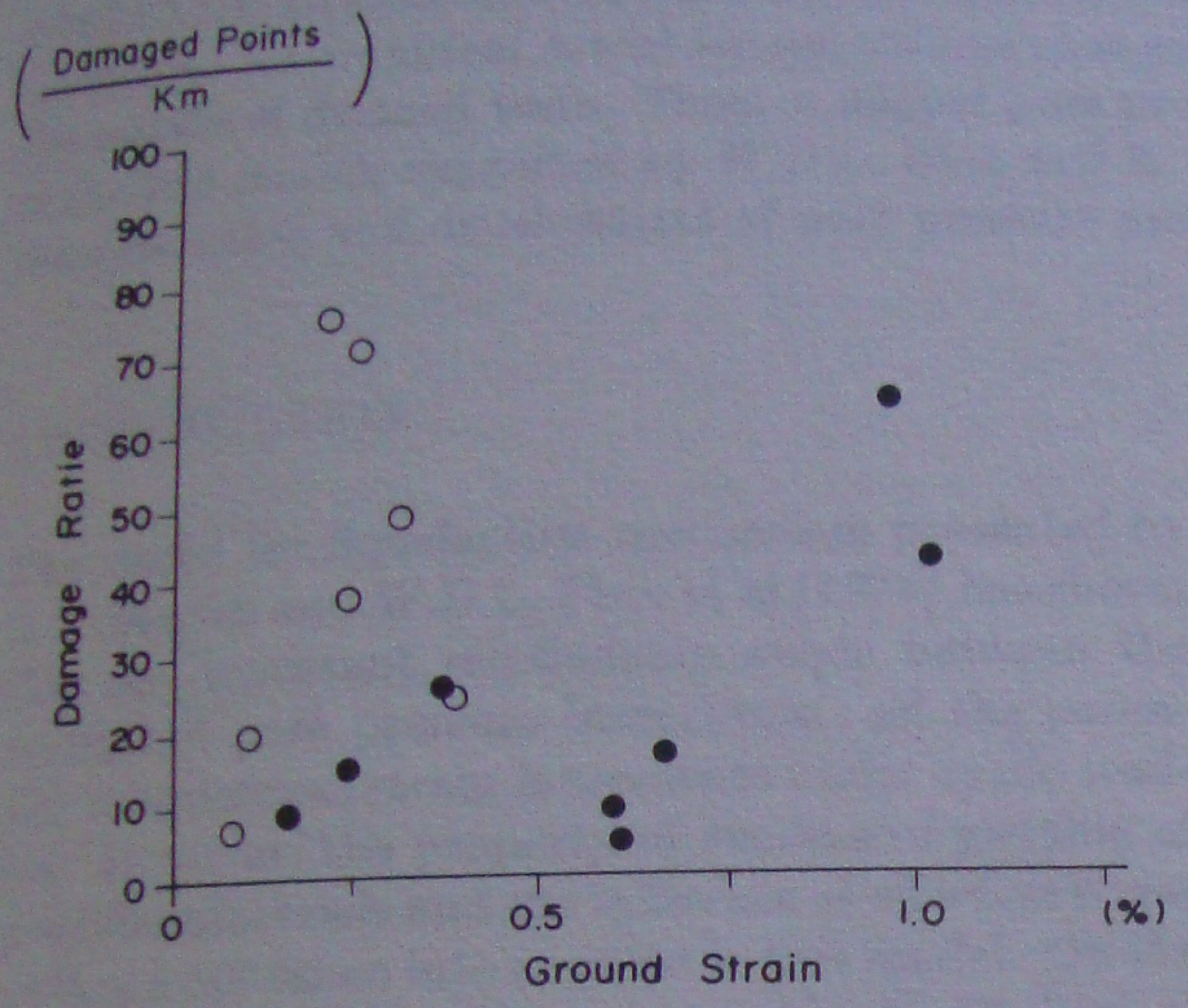

Fig. 17 Damage rate of gas pipe (Ø=75 - 150 mm, ● Steel Pipe, ○ Cast Iron Pipe)

75 to 150 mm, where the abscissa is the maximum absolute value of the two principal ground strains. It is also recognized that a certain correlation can be found between the damage rate to buried gas pipes and the permanent ground strains.

6 CONCLUSIONS

The following results were obtained about the influential factors to the magnitude of the permanent ground displacements and about the correlation with the damage to the buried pipes, etc.:

(i) The gradients of the ground surface and the lower boundary face of the liquefied layer, and the thickness of the liquefied layer have considerable influence on the magnitudes of the permanent ground displacements.

(ii) A certain high correlation was found between the magnitudes of the permanent ground displacements and the damage rate to houses.

(iii) A relatively high correlation of the magnitudes of the ground displacements with the damage rate to large diameter (75 -150mm) steel and cast iron gas pipes was recognized, but not with those of small diameter (32-50mm) steel gas pipes and asbestos cement water pipes. This result shows that because the strength of the small diameter gas pipes and asbestos cement water pipes was generally low, if the damage was not due to the permanent ground displacements, then it could be due to other causes such as local ground failures induced by liquefaction and the relative displacements by the water propagation.

(iv) The permanent ground strains, calculated from the measured permanent ground displacements reached about 4% in Niigata City and 1.5% in Noshiro City.

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