4 . Analysis of Relationship between Magnitudes of Permanent Ground Displacements, and Geological and Topographical Conditions

In Chapters 2 and 3, the permanent ground displacements and the resultant damage to structures in Noshiro City during the 1983 Nihonkai-Chubu earthquake as well as in Niigata City during the 1964 Niigata earthquake were studied. Furthermore, the causes of permanent ground displacements were discussed qualitatively by examining the geological and topographical conditions.

The types of permanent ground displacements caused by soil liquefaction during the two earthquakes can be summarized as shown in Figure 4-1. Case A depicts the type of the displacements that occurred in Noshiro City ; the ground surface is slightly inclined and the liquefied layer exists along the surface. Cases B and C depict the types found in Niigata City. Case B shows that the ground surface is flat on the land but has an abrupt vertical discontinuity at revetments of the river, and the lower boundary face of the liquefied layer is inclined towards the river center. Case C was found in the area around the Niigata Railway Station and Hakusan Park, where the ground surface is almost horizontal but the lower boundary face of the liquefied layer is inclined.

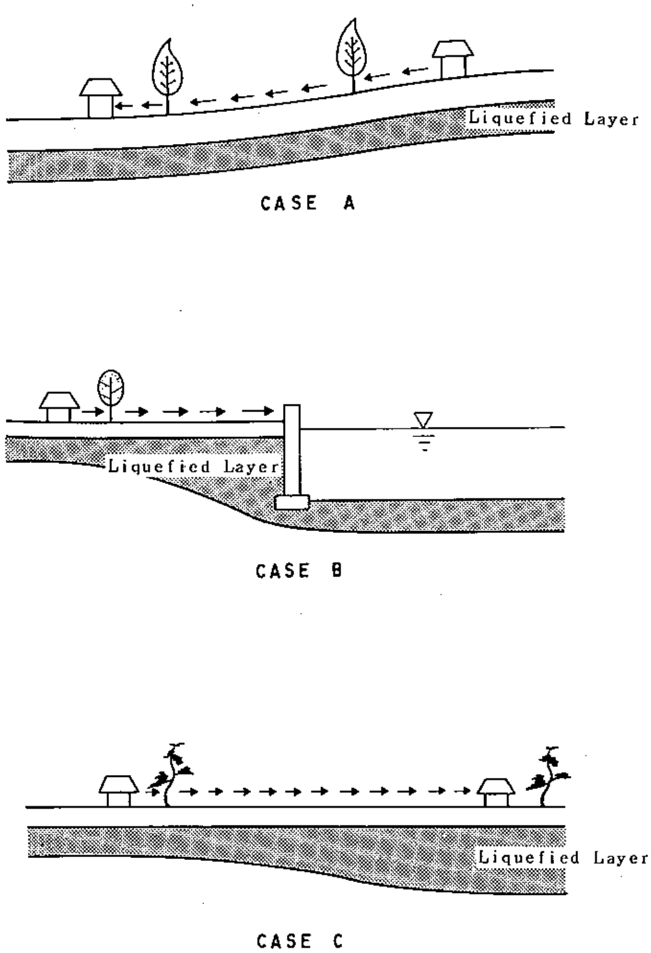


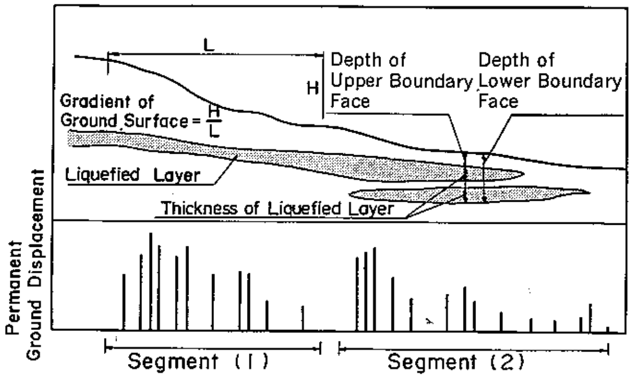
Fig. 4-1 Types of permanent ground displacements

In this chapter, the factors influencing the magnitude of the horizontal ground displacements are quantitatively analyzed and a formula for evaluating the permanent ground displacement is proposed.

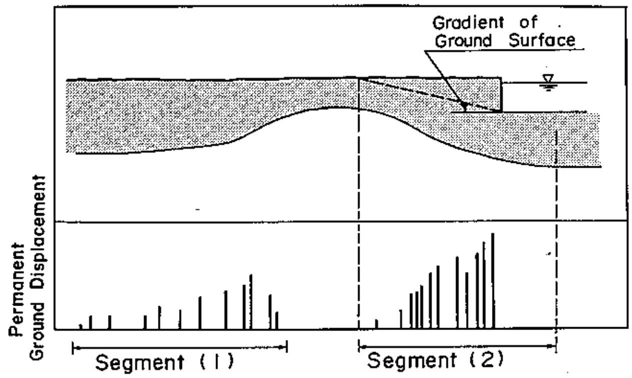
The analysis in this chapter includes the data of permanent ground displacements by the 1971 San Fernando earthquake in addition to the data by the Nihonkai-Chubu and Niigata earthquakes. The permanent ground displacements that occurred in the vicinity of the Upper Van Norman Lake during the San Fernando earthquake are summarized in Appendix IV, mainly quoting from references (5), (6), (16), and (17).

4 . 1 Study of factors influencing magnitudes of permanent ground displacements

The following factors, shown in Figure 4-2 (a), were considered for the analysis on the correlation



(a) Factors of liquefied soil layer and topography



(b) Gradient of ground surface along the Shinano River

Fig. 4-2 Factors of liquefied soil layer condition and topography for quantitative analysis

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).

(v) Minimum value of Factor of Liquefaction Resistance F_L. (Appendix III)

(vi) Index of Liquefaction Potential P_L. (Appendix III)

The liquefied soil layer was conjectured by a method proposed by Iwasaki and the others.[7] The soil layer with the Factor of Liquefaction Resistance F_L less than 1.0 was considered to have been liquefied.

These factors were determined from each soil layer profile drawn along the sections, shown in Figure 3-12 and Appendixes IV and V, according to the following procedure.

(i) The established sections were divided into segments as shown in Figure 4-2, 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. Along the Shinano River bank, the area between the center of the river and the point at which the lower boundary face of the liquefied layer becomes horizontal is considered as one segment, as shown in Figure 4-2 (b).

(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 Figure 4-2 (a), 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 Figure 4-2 (b).

A total of 27 sections in Noshiro City and 5 sections in Niigata City were established as shown in Figures 2-10 and 3-2.

Figure 4-3 shows the relationship between the ground surface gradient 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 the 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.

Figure 4-4 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

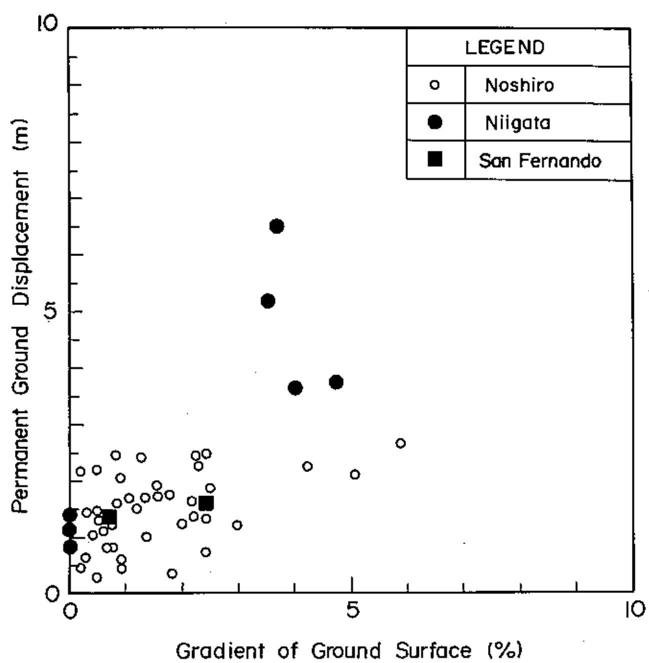


Fig. 4-3 Relationship between the gradient of ground surface and the magnitude of permanent ground displacement

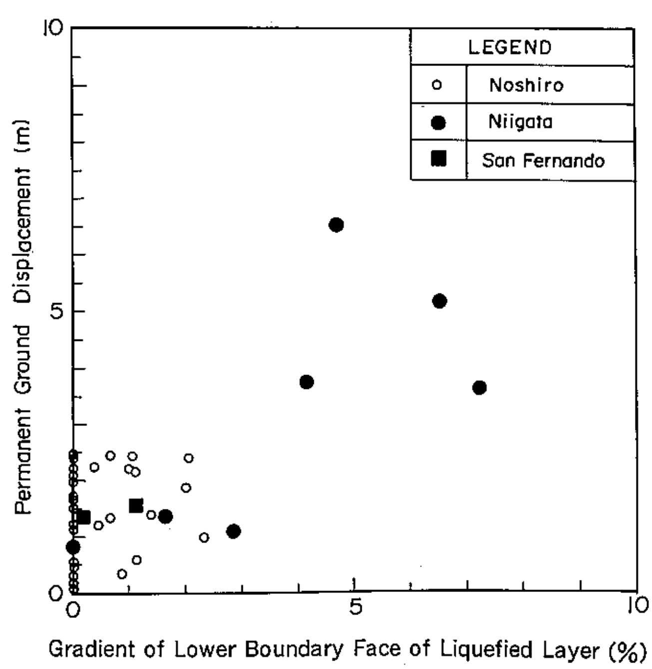


Fig. 4-4 Relationship between the gradient of lower boundary face of liquefied layer and the magnitude of permanent ground displacement

displacements were mainly governed by the gradient of the ground surface.

Figure 4-5 shows the relationship between the displacements and the gradient of the liquefied layer's upper boundary face, and also Figure 4-6 shows the correlation with the mean gradient of the ground surface throughout the whole slope along the section lines shown in Figures 2-10 and Appendix IV.* However, no clear causal relationship can be found between the displacements and these two factors.

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 in the cases of the Nihonkai-Chubu and the Niigata earthquakes, respectively. 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 as mentioned in the beginning of this chapter.

Figure 4-7 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 Figures 4-3 and 4-4 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.

Figure 4-8 shows that the correlation of the magnitudes of the permanent ground displacement

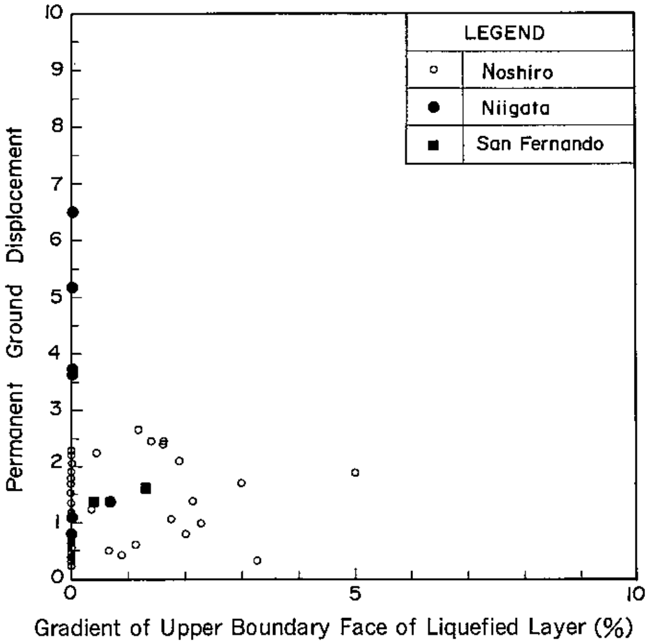


Fig. 4-5 Relationship between the gradient of upper boundary face of liquefied layer and the magnitude of permanent ground displacement

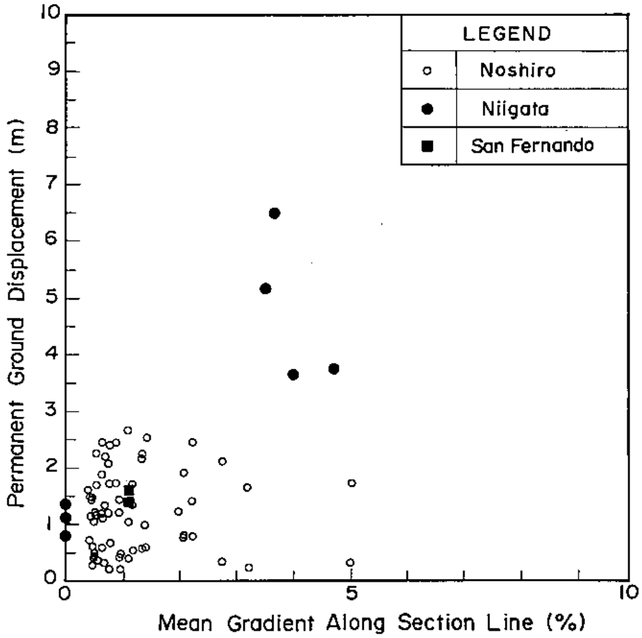


Fig. 4-6 Relationship between the mean gradient of ground surface and the magnitude of permanent ground displacement

* In the case of Niigata City, the gradients shown in Fig. 4-6 were determined from the segments of the slope, same with the ones in Fig. 4-3.

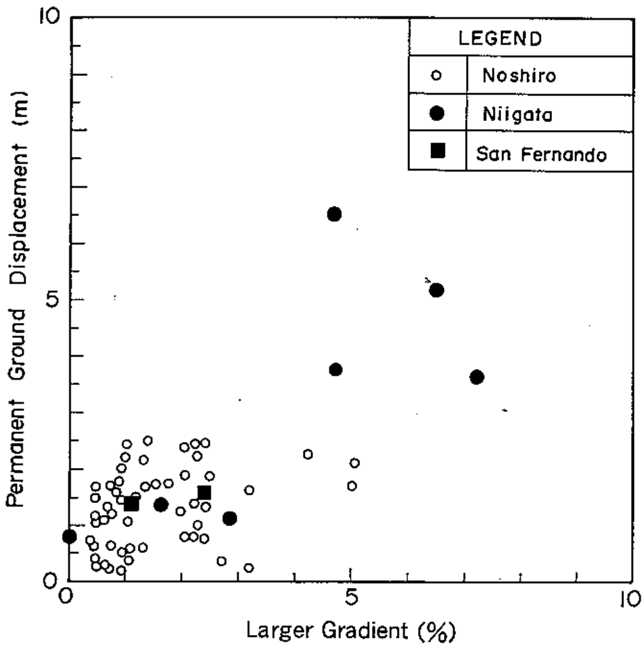


Fig. 4-7 Relationship between the larger value of the ground surface gradient and the lower boundary face gradient of liquefied layer, and the magnitude of permanent ground displacement

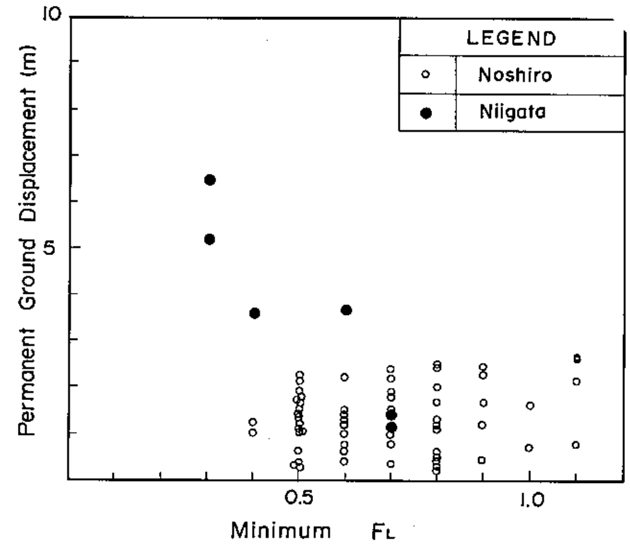


Fig. 4-9 Correlation of the displacement magnitude with the minimum value of Liquefaction Resistance Factor, F_L

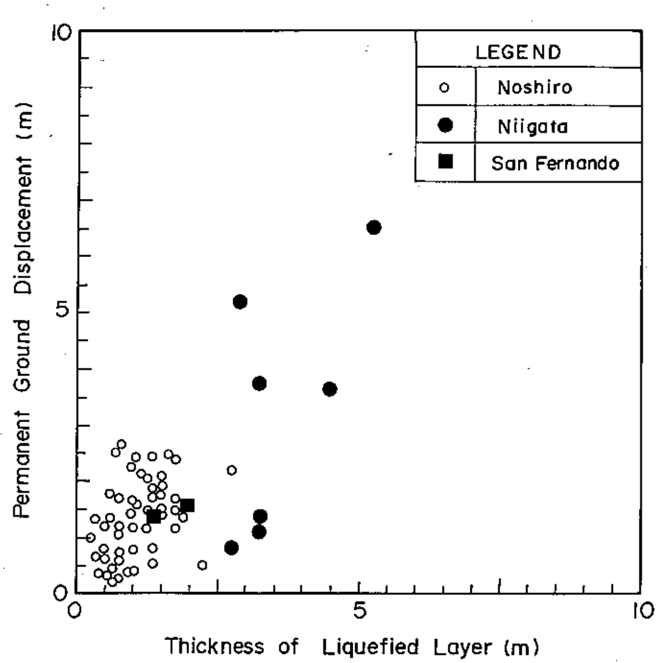


Fig. 4-8 Relationship between the magnitude of permanent ground displacement and the thickness of liquefied layer

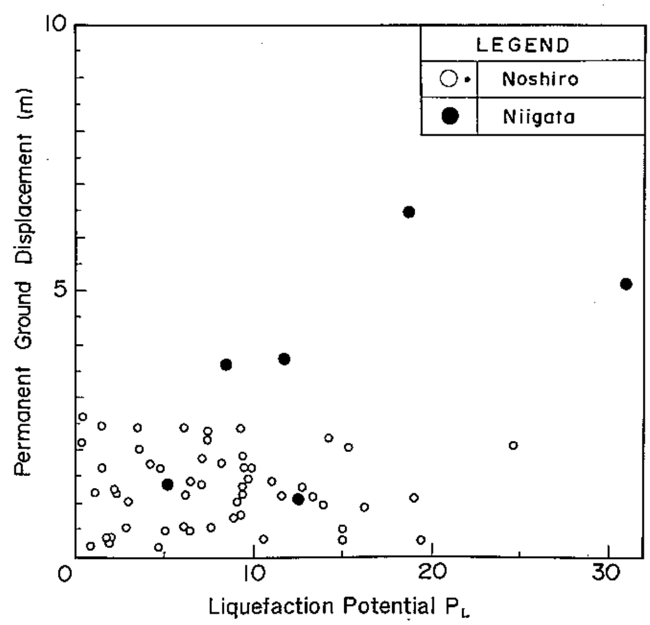


Fig. 4-10 Correlation of the displacement magnitude with Index of Liquefaction Potential, P_L

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. As will be mentioned later in the numerical analysis of damaged RC piles in Chapter 6, permanent ground displacements are surmised to be caused not by sliding on only one particular slip plane in the soil layer, but by shearing deformation throughout the liquefied layer. The result shown in Figure 4-8 qualitatively coincides with the above conjecture.

Figures 4-9 and 4-10 show the correlation of the displacement magnitude with the minimum value of the Liquefaction Resistance Factor F_L* and the Index of Liquefaction Potential P_L*. These figures do not include any data from the 1973 San Fernando earthquake because of insufficient references regarding N values (blow count of standard penetration test) and grain size characteristics.

No clear correlation of the permanent ground displacements can be found with the F_L and P_L. As shown in Appendix III, the Index of Liquefaction Potential, P_L, was obtained by an integration of F_L in the vertical direction, and therefore is an index dependent upon the thickness of the liquefied layer. Consequently, since the thickness of liquefied layer had a comparatively high correlation with the magnitudes of the permanent ground displacements, as shown in Figure 4-8, some correlation with P_L should be expected.

In the case of Noshiro City, the value of P_L ranges from 0 to 25, and no correlation can be seen with the permanent ground displacements. On the other hand, the few data from the Niigata earthquake show a somewhat high correlation between the displacements and the Index of Liquefaction Potential, P_L. This is considered to be due mainly to the fact that the distribution of liquefied layer in Niigata City is relatively simple, and P_L is roughly proportional to the thickness of the liquefied layer; whereas in Noshiro, the distribution of the liquefied layer is complex, and in addition, some engineering judgements were made for the definition of liquefied layer thickness. For example, when the estimated liquefied zone was divided into more than one layer, the thickness of the intermediate layer was also added to the total thickness.

4.2 Regression analysis of magnitudes of permanent ground displacements

In the previous section, 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.

In this section, a regression analysis of the magnitude of permanent ground displacements using the above two factors is conducted.

The following regression formula is considered:

$$D = a \cdot H^m \cdot \theta^n$$

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 (%)
- a,m,n : Regression constants.

* The Liquefaction Resistance Factor, F_L, and the Index of Liquefaction Potential, P_L, are outlined in Appendix III. F_L is defined in each layer of the soil, while P_L is defined as being one of the mean values of F_L, along with the depth.

By using 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 is established.

$$D \fallingdotseq 0.75 \cdot H^{0.48} \cdot \theta^{0.33}$$

By rounding off the values of the above regression coefficients for the convenience of practical use, the next formula is obtained.

$$D \fallingdotseq 0.75 \cdot \sqrt[2]{H} \cdot \sqrt[3]{\theta}$$

Figure 4-11 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.

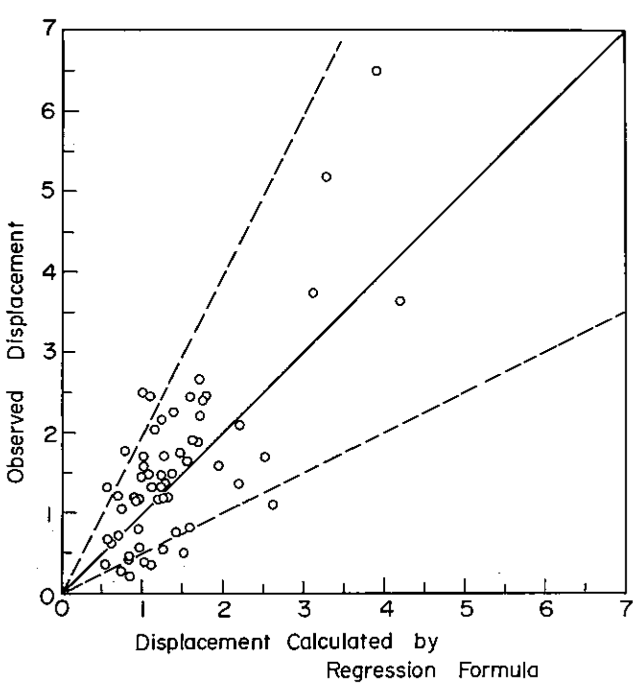


Fig. 4-11 Comparison of the permanent ground displacement estimated by regression formula with the observed ground displacement

The regression formula of permanent ground displacement shown above was developed based on the limited data obtained from the Nihonkai-Chubu, the Niigata, and the San Fernando earthquakes. The formula is considered to be strongly affected by the data from Noshiro City, where sliding occurred along gentle slopes (gradients of less than 5%), in the range where the magnitude of displacement is smaller than 5.0 m. On the other hand, the formula is heavily dependent upon the data from Niigata City, where large displacement occurred along the river bank, in the range of displacements above 5 m.

As mentioned above, the proposed formula was developed by combining the data on different types of ground displacements, and should be improved by the accumulation of more data in the future.

The formula, as a matter of course, cannot be applied to the collapses of embankments and slopes. Furthermore, because the soil layers in Noshiro and Niigata consist of relatively uniform medium grain size sand, some care must be taken when applying the formula to the ground containing fine sand.