7 . Conclusions

The liquefaction induced permanent ground displacements during the 1983 Nihonkai-Chubu and 1964 Niigata earthquakes were measured in Noshiro City and Niigata City, respectively, using the aerial photographs taken before and after the earthquakes.

The mechanism of generation of the permanent ground displacements due to liquefaction was discussed, based on the geological and the topographical conditions and the factors influencing the magnitudes of the displacements were investigated.

Furthermore, the causal relationship of the ground displacements with the damage to bridges, revetments of river, buried pipes, houses, etc., were studied. The major results are summarized below:

(1) **Measurement of Permanent Ground Displacements by Aerial Survey**

(i) In Noshiro City during the 1983 Nihonkai-Chubu earthquake, the permanent ground displacements with a maximum horizontal amplitude of 5.0 m were caused over a vast area on the gentle slopes of the sand dunes, where houses and buried pipes were severely damaged. Numerous ground failures such as cracks, sand volcanoes, subsidences, and risings were found in the area where the permanent ground displacements were dominant, and the directions of the cracks of the ground were mostly perpendicular to those of the permanent ground displacements.

(ii) In Niigata City during the 1964 Niigata earthquake, most of the Shinano River bank slid toward the river at a maximum horizontal displacement of 8.8 m, causing serious damage to bridges, revetments of the river, etc. These large displacements along the river channel were confirmed by the fact that the river width had been reduced by 7～23 m, which was obtained by aerial surveys using two photographs: one taken in 1962 which is 2 years before the earthquake and the other taken in 1971, by which time the revetments had been completely restored. Furthermore, another instance of ground displacements of about 2.0 m were observed near the Niigata Railway Station although the ground surface was mostly flat.

(iii) Based on the geological and the topographical investigations in the areas where the permanent ground displacements were observed, it was summarized that three types of ground displacements may have occurred (as shown in Figure 4-1) .

The first type was observed in Noshiro City, where the ground surface was slightly inclined and liquefied layers existed along the surface. The second one was found in the area along the Shinano River, where the ground surface was flat on the land, but had an abrupt vertical discontinuity at the revetments of the river, and the liquefied layer was inclined. The last type of the permanent ground displacements was observed in the area around the Niigata Railway Station, where the ground surface was horizontal but the liquefied layer was inclined.

(2) Investigation into Causal Relationship between Permanent Ground Displacements and Damage to Structures

The causal relationship between the damage to bridges, revetments of the river, foundation piles of a building, etc., and the measured permanent ground displacements during the 1964 Niigata earthquake was discussed.

(i) It can be concluded that the permanent ground displacements due to liquefaction was more probable for the cause of the collapse of the Showa Bridge than the inertia force by the earthquake motion, by taking into consideration the estimated liquefied layer of the vicinity, the deformation of the steel piles, and the witnesses' observations about the collapse.

(ii) The damage to the abutment and the piers of the Yachiyo Bridge can also be explained by the permanent ground displacements of 2 to 4 m toward the river.

(iii) Since the damage to the revetments of the river was caused mostly in the area where the permanent ground displacements were dominant, it can be considered that the ground displacements were the main factor governing the damage.

(3) Study of Causes of Permanent Ground Displacements

Based on the geological and the topographical conditions, the mechanism of the generation of the permanent ground displacements was investigated and the influences of gradient of ground surface, depth and thickness of liquefied layer, and degree of liquefactions, on the magnitudes of the displacements were analyzed.

(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) The following formula was obtained from a regression analysis of magnitudes of the permanent ground displacements:

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

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 of the lower boundary face of the liquefied layer (%)

(4) Correlation Analysis of Damage Rate to Buried Pipes and Houses with Permanent Ground Displacements and Strains

The correlation of the damage rate to houses and buried gas and water pipes with the magnitudes of the permanent ground displacements as well as with the permanent ground strains, which were calculated from the measured displacements, was investigated.

(i) A certain high correlation was found between the magnitudes of the permanent ground displacements and the damage rate to houses. However, it should be noted that there were some cases where the damage rate was high even though the displacement was small, because the houses were damaged only by local failures of the foundation ground such as cracks and subsidences due to liquefaction without large displacements.

(ii) A distinct correlation of the magnitudes of the ground displacements with the damage rate to large diameter (75-150 mm) steel and cast iron gas pipes was recognized, but not with those of small diameter (32-50 mm) steel gas pipes and asbestos cement water pipes. Most of the damage to small diameter gas pipes was caused at screw joints and T-shape joints. This result shows that because the strength of these small diameter gas pipes and asbestos cement water pipes was generally low the damage could have occurred due to other causes such as local ground failures induced by liquefaction and the relative displacements by the wave propagation, if not due to the permanent ground displacements.

(iii) The permanent ground strains, calculated from the measured permanent ground displacements reached about 4% in Niigata City and 1.5% in Noshiro City. A clear correlation was also found between the damage rate to large diameter steel gas pipes and the magnitudes of the ground strains.

(5) Numerical Analysis of Failure Process of Foundation Piles and Buried Pipe

The failure processes of RC piles and steel gas pipe damaged by the 1964 Niigata and 1983 Nihonkai-Chubu earthquakes, respectively, were investigated by numerical analyses. Furthermore, based on these analyses, the vertical distributions of the permanent ground displacements in the horizontal direction, the friction strength between the liquefied soil and pipes were discussed.

(i) The permanent ground displacements have a much higher probability to be the direct cause of the damage to the RC piles than the inertia force of the superstructure.

(ii) The damage to the steel gas pipe can be explained well by the permanent ground displacements measured in the neighborhood of the damaged point. And it was assumed that the friction strength between the pipe and the ground had reduced to a large degree.