1 . Introduction

During past large earthquakes, the liquefaction of sandy ground has been one of the main causes of damage to various types of structures such as bridges, embankments, buildings, houses, lifeline facilities, etc. This damage includes the followings:

(i) Settlement and tilting of structures due to a reduction in the bearing capacity of the foundation soil.

(ii) Floating of underground structures in the liquefied soil layer due to buoyancy.

(iii) Failure of retaining walls, quaywalls, etc., due to large increase in earth pressure.

(iv) Failure of earth structures such as embankments due to decreases in the strengths of sandy soil materials.

In addition to the damage mentioned above, which can be caused by liquefaction of the foundation ground and/or the soil materials of structures, the damage due to landslides and large permanent ground displacements caused by liquefaction over a wide area has been recognized during the past disastrous earthquakes.

It was deduced from the investigations into the damage to bridge piers and revetments of the Shinano River during the 1964 Niigata earthquake[(1)] that an expanse of ground along the river moved several meters toward the river. In Noshiro City during the 1983 Nihonkai-Chubu earthquake,[(2),(3)] the numerous cracks and sand volcanoes on the gentle slopes of the sand dune suggested that some sliding had occurred due to soil liquefaction, causing severe damage to the residential area of the city.

It was also reported that during the 1964 Alaska earthquake,[(4)] a vast area along the Pacific coast of Valdez City slid due to liquefaction of sandy soil, and that during the 1971 San Fernando earthquake,[(5),(6)] a gently sloped ground surface in the vicinity of the Upper Van Norman Lake slid 2 to 3 m toward the lake due to liquefaction of a loose silty sand layer.

From the examinations into the damage to structures in the liquefied area during these earthquakes, it can be assumed that a considerable part of the damage was caused by the large permanent ground displacements. Therefore, in the earthquake resistant design of structures on and in the ground with a high probability to be liquefied, it is required to take the large permanent ground displacements into consideration in addition to the effects of liquefaction mentioned in (i)-(iv).

However, it seems that no sufficient research on the permanent ground displacements due to liquefaction has been conducted mainly due to lack of quantitative data about ground deformations.

The authors conducted measurements of the permanent ground displacements caused by the 1983 Nihonkai-Chubu earthquake in Noshiro City as well as by the 1964 Niigata earthquake in Niigata City, and discussed the causes of the ground displacements based on the geological and the topographical conditions.

Furthermore, the causal relationship of the ground displacements with the damage to bridges, revetments of river, buried pipes, houses, etc., are studied.

The main subjects of this report are summarized below :

(i) **Measurement of Permanent Ground Displacements (Chapters 2 and 3)**

Permanent ground displacements caused by the 1983 Nihonkai-Chubu earthquake were measured in Noshiro City, where most of the urban area suffered serious damage to houses, buildings, and lifeline facilities due to soil liquefaction, using pre- and post-earthquake photographs.

In the same way, the permanent ground displacements by the 1964 Niigata earthquake were measured mainly in the area along the Shinano River, where severe damage to bridges, revetments of the river, etc., had been reported. The relationship of the measured displacements with the distribution of ground failures such as cracks, subsidences, and risings was investigated. Furthermore, the characteristics of the permanent ground displacements are qualitatively discussed based on micro-topographical conditions.

(ii) **Investigation into Causal Relationship between Permanent Ground Displacements and Damage to Structures (Chapters 2 and 3)**

By referring to existing reports on damage to buried pipes, bridge piers, revetments of the river, foundation piles, houses, etc., by the two earthquakes, the causal relationship between the measured permanent ground displacements and the damage was examined.

(iii) **Study of Causes of Permanent Ground Displacements (Chapters 2, 3, and 4)**

Based on the results of soil condition surveys performed on the two areas where permanent ground displacements were measured, the mechanism of the generation of permanent ground displacements was investigated.

Furthermore, the influential factors of the geological and the topographical conditions, such as gradient of the ground surface, thickness of the liquefied layer, etc., on the magnitudes of the ground displacements were quantitatively analyzed by adding the data from the 1971 San Fernando earthquake to those from the two earthquakes in Japan. Finally, based on a regression analysis, a formula for estimating the magnitude of the ground displacements was established.

(iv) **Correlation Analysis of Damage Rate to Buried Pipes and Houses with Permanent Ground Displacements and Strains (Chapter 5)**

The correlation of the damage rates to buried pipes and houses, 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.

(v) **Numerical Analysis of Failure Process of Foundation Piles and Buried Pipe (Chapter 6)**

The failure processes of reinforced concrete piles and steel gas pipe damaged by the 1964 Niigata and 1983 Nihonkai-Chubu earthquakes, respectively, were investigated by numerical analyses, considering the permanent ground displacements measured in the surrounding area.

Based on these investigations the vertical distributions of the permanent ground displacements and the friction strength between the liquefied soil layers and the buried pipe were also discussed.